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February 1972

IDA

SCIENCE AND TECHNOLOGY DIVISION

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ABBREVIATIONS

AAS	atomic absorption spectroscopy
AC	alternating current
ARPA	Advanced Research Projects Agency, Department of Defense
CRT	cathode ray tube
CW	continuous wave
DC	direct current
DOT	Department of Transportation
ECOM	Electronic Command, Department of the Army
EDNA	ethylene dinitramine
EXP. D	ammonium picrate
FAA	Federal Aviation Administration
FLIR	forward-looking infrared
FRC	Federal Radiation Council
GC	gas chromatograph
GSD	Genetically Significant Dose
HMX	cyclotetramethylenetetranitramine
IDA	Institute for Defense Analyses
IF	intermediate frequency
IITRI	Illinois Institute of Technology Research Institute
IR	infrared
kvp	kilovolts peak
LIDAR	laser light detecting and ranging
LWL	Land Warfare Laboratory, Department of the Army

MERDC	Mobility Equipment Research and Development Center, Department of the Army
MTF	modulation transfer function
NCRH	National Center for Radiological Health
NCRP	National Council on Radiation Protection
NEM	noise-equivalent modulation
NEP	noise-equivalent power
NG	nitroglycerin
PETN	pentaerythritol tetranitrate
ppb	parts per billion
ppm	parts per million
rad	radiation absorbed dose
RBE	relative biological effectiveness
RDX	cyclotrimethylenetrinitramine
rem	roentgen equivalent, man
R&D	research and development
SCR	strip chart recorder
TC	thermocouple
TETRYL	trinitrophenylmethylnitramine
TI	Texas Instruments, Incorporated
TNETB	trinitroethyl trinitrobutyrate
TNT	trinitrotoluene
TSC	Transportation Systems Center, Department of Transportation

CONTENTS

SUMMARY

This report surveys technologies for protecting aircraft against hijacking and the unlawful boarding of explosives, briefly examines the use of nonlethal weapons in hijacked aircraft, and recommends R&D actions to strengthen anti-hijack defenses. The report is an updating and expansion of IDA Study S-332, "On the Detection of Concealed Handguns" (Ref. 1).

The overall study was divided into two parts: technology and operations. The examination of current operations is reported in a companion paper, IDA Paper P-806, "Airline Hijackings: Analysis of a Decade of Experience and Some Interim Procedural Solutions" (Ref. 2).

A. FINDINGS

From among the promising techniques surveyed, we have selected those that afford the most readily available capabilities and we have selected the program directions most likely to yield new capabilities. Some of our evaluations are necessarily judgmental because experimental data are lacking concerning the relative effectiveness of some sensors. Furthermore, in this report, we have considered feasibility more than the practical problems of using the resultant devices at airports.

Table 1 offers a comparison of the various sensory techniques investigated and indicates recommended R&D program elements. The actual or postulated applicability of each technique to the detection of weapons or explosives is considered. "Probability of Detection" refers to estimated capability after needed research and development is essentially completed. The estimated costs shown under "Research" are for those activities listed under "Recommended Program Elements"

TABLE 1. SUMMARY COMPARISON OF DETECTION TECHNIQUES AND RECOMMENDED PROGRAM ELEMENTS

Technique	Detection of		Probability of Detection	False-Alarm Probability	Estimated Cost, thousands		Recommended Program Elements	Discussed at Page
	Weapons	Explosives			Research	Sensor (Each)		
Nonimaging								13
Physiological Observation	•	•	Low, Low	High, High	$ --	$ --	None.	13
Dogs	?	•	?, Medium	?, Medium	200	2	Test and train.	15
Mass Detection	•		Low	High	--	--	None.	18
Microwave and Millimeter-Wave Detection								19
Radar	•		Low	High	--	--	None.	19
Radiometry	•		Low	High	--	--	None.	19
Radar-Radiometry	•		Medium	Medium	100	?	Measurements.	26
High Range Resolution Radar	•		Medium	Medium	100	?	Measurements.	26
Chemical Detection								29
Sniffers		•	Medium	Low	200	15	Monitor.	38
Neutron Activation		•	High	Low	300	?	Engineering, test.	55
Metal Detection	•		High	Medium	200	20	Measurements and analysis.	59
Imaging								71
Television in the Visible Spectrum	•		Low	Low	--	--	None.	71
Magnetic Mapping and Display	•		Low	?	--	--	None.	71
Ultrasonics	•		Low	Low	--	--	None.	72
X Rays	•		High	Low	200	25	Establish dose limits, flying spot for people.	75
Radar								93
Millimeter-Wave Lens System	•		Medium	Medium	100	100	Monitor.	95
Millimeter-Wave Holography	•		Medium	Medium	100	50	Measurements.	99
Infrared	•		Medium	Low	100	100	Measurements.	103

and do not represent the entire R&D cost required to obtain an operational prototype. Estimates of measurement costs assume that instrumentation is already available at no expense.

For the detection of explosives, the only techniques showing any capability are the use of dogs, chemical analysis, and neutron activation. Much needs to be learned about dogs' sensitivity to vapors of explosives and how to train and maintain their efficiency for detection. Chemical vapor sensor programs are under way at LWL and MERDC. Fast neutron activation analysis studies are under way and the use of thermal neutrons appears as a new possibility.

For the detection of weapons, particularly handguns, metal sensing techniques continue to offer the most promise when performance, cost, safety, and availability are all considered. Evidence of possible improved gun detection capabilities from multiple-measurement metal detection devices is still inadequate. X-ray techniques still offer the best of the imaging possibilities but impose a small X-radiation dose ($\sim$ 0.1 mrad). Imaging radar and IR in the 100- to 1000-micron wavelength range offer interesting new possibilities, but information is needed to determine whether these techniques can penetrate clothing in times short enough to be operationally useful.

Some of the techniques that offer, at present, no prospect for use in the aircraft protection context are physiological observations, mass detection, nonimaging microwave and millimeter-wave radar and radiometry, conventional television, magnetic imaging, and ultrasonic imaging.

Of the nonlethal weapons surveyed for aircrew and skymarshal use against hijackers, the Taser electric shock weapon and chemical Mace appear to merit consideration.

B. RECOMMENDATIONS

The recommendations in this report are addressed to the FAA with the goal of developing techniques that could reduce the likelihood of

airliner hijacking and the illegal boarding of explosives on aircraft. Our recommendations are based on our appraisal of future operational capabilities, on some consideration of R&D, acquisition, and operating costs, and on an implicit (and perhaps very subjective) assessment of operational utility. They are arranged below under each heading in the order of their priority.

1. Explosives Detection

The following activities are recommended in the area of explosives detection:

1. The program to appraise the capabilities of dogs (and dog training) should be expanded, drawing on ongoing programs in the United States.
2. The fast neutron activation analysis programs for examining packages and luggage should be expanded. Further, an alternate technique using thermal neutrons should be given a feasibility evaluation test.
3. Work by the Department of the Army on chemical analyses of explosives' vapors could become important and should be monitored and supported to ensure consideration of airport application.

2. Weapons Detection

The following activities are recommended in the area of weapons detection:

1. As X ray is the only technique that offers immediate promise of gun detection without frisking, one or two flying-spot, scanning X-ray devices designed to examine humans should be constructed. At one or two large airports procedures should then be developed and tested to facilitate the use of such devices to inspect volunteers and to determine their operational effectiveness and false-alarm characteristics.

2. Experimental measurements and tests should be undertaken to determine the spectral transmittance of clothing at wavelengths from 100 to 1000 microns. This program should be accompanied by a determination, at the same wavelengths, of the emissivity of weapons and the human epidermis to establish the required IR system sensitivity.

3. Experimental measurements and tests should be undertaken to develop an automated, scanning X-ray contrast system of low dosage (< 0.1 mrad) for the detection of bullets and handguns on people and in baggage.

4. Experimental measurements and tests should be undertaken to initiate a new and expanded program to establish the capabilities of metal detector systems. This program should be accompanied by a theoretical analysis of the magnetic perturbations of a variety of metallic shapes to aid in establishing sensitivity limits and instrumentation approaches.

5. Experimental measurements and tests should be undertaken to determine the feasibility of millimeter-wave holographic systems for detecting and distinguishing concealed metallic weapons.

6. Experimental measurements and tests should be undertaken to evaluate the performance of liquid-helium-cooled detectors in a passive imaging IR system or the performance of a laser with uncooled detectors in an active imaging system.

3. Nonlethal Anti-Skyjacker Weapons

To improve the safety of the anti-skyjacker weaponry available to aircrews and skymarshals, it is recommended that:

1. The Taser electric shock weapon be thoroughly tested as to hazard, effectiveness, and operational utility in providing an instantaneous knockdown capability.

2. Range and aiming characteristics of the Taser weapon be measured. If the Taser proves accurate, it could serve as an alternative to the gun in knockdown power.

3. Mace could serve as a further option. There is little need for further research and development on Mace.

I. INTRODUCTION

This report presents our investigation of the technical promise and feasibility of various methods of protecting aircraft against hijacking and the unlawful boarding of explosives. Our recommendations for future research and development are included.

A. BACKGROUND

In 1968, following Senator Robert Kennedy's assassination, IDA was asked to investigate means of detecting concealed handguns. The impetus for the study reflected the manner of Senator Kennedy's death, and the results (Ref. 1) were to assist in the future protection of public figures. Existing capabilities were surveyed, and a program of measurements, research and development was recommended.

More recently, the Federal Aviation Administration (FAA) of the Department of Transportation (DOT) asked IDA to update the earlier study, expanding it to cover weapons detection and devoting particular attention to means of reducing airliner hijacking. Specifically, the statement of work (Appendix A) divided the study into five parts:

a. Detection of guns and other concealed weapons
b. Detection of explosives
c. Operational aspects
d. Airline experience
e. Nonlethal weapons for aircrew use.

This technology report responds to parts a, b, and e of the work statement. A companion report (Ref. 2) discusses the operational aspects and airline experience over the last decade.

In the earlier study on detection of concealed handguns the principal development programs recommended were for magnetic detectors coupled with new, very short-pulse X-ray equipment. Additionally, it was recommended that several measurement test programs (including measurements of false-alarm characteristics) be undertaken under simulated operational conditions. Included were:

- Test feasibility of chemical methodologies (e.g., "sniffing").
- Measure ultrasonic absorption and reflection characteristics of clothing and weapons.
- Measure infrared (IR) transmission of clothing in the 0.7- to 8-micron region.
- Measure weapon and body reflectivities with millimeter radar having a resolution of approximately 1 cm.

As will be seen in this report, there has been progress in all these areas, and some new possibilities have appeared. Improved metal detectors and new X-ray equipment are now available (the latter is somewhat different than envisaged in Ref. 1). An explosives "sniffer" is now on the market. Some ultrasonic measurements have been carried out and, as expected, have indicated that ultrasonic techniques are unlikely to be useful. IR measurements have confirmed that absorption is generally excessive in the 0.7- to 8-micron region but that transmission through clothing is much greater in the 200- to 500-micron region. Work on radar for gun detection has been modest, but some new data have been obtained and new possibilities are beginning to emerge.

B. REPORT ORGANIZATION

This report reviews the state of all the above approaches to a defense against aircraft hijacking or bombing, and, in addition, it examines a number of other technologies that have not shown great promise so far. Protection against potential hijackers and the boarding of explosives involves inspection and control procedures at a limited number of access points--the ticket counter, the boarding gate,

and the baggage entrances. Screening techniques can be divided into two categories: imaging and nonimaging. Conventionally, imaging techniques have low false-alarm rates but require an observer. Nonimaging sensors have higher false-alarm rates but can be designed to provide a simple alert signal (e.g., a flashing light or a buzzing sound). Nonimaging techniques, including physiological observation, dogs, mass detection, radar, chemical analysis, and metal detection, are discussed in Section II. Imaging systems, including conventional television, magnetic field distortion displays, ultrasonics, X rays, radar, and infrared, are treated in Section III. Section IV discusses the prospects for use of nonlethal weapons on board an aircraft in the event that a hijack occurs. A recapitulation (Section V) concludes the report. A classified annex gives a brief description of a technique which, as it turns out, has little prospect for application to weapons detection in the anti-hijacking context.

C. AIRLINER HIJACKING HISTORY

Before we discuss prevention technology, a note (drawn from Ref. 2) about the hijacking threat is in order. Since 1968 there has been an average of two hijack attempts each month, or just over 25 a year. Of 108 hijack attempts against scheduled U.S. passenger aircraft in the ten-year period from May 1961 through August 1971, 78 were successful in the sense that the aircraft were diverted to destinations not in their original schedules. (In some of these cases the hijackers were apprehended.) Havana was named as the desired destination in 79 cases, no specific destination was given in seven cases, and a variety of destinations were specified (Cairo was named three times) in the other cases. Seventy-eight of the hijackings were attempted by men working alone, although there were at least 130 men involved in all the incidents. In addition, 17 women took part, and one of them actively conducted a hijack herself. Nineteen pre-teen-age children were also involved, but they appear to have played minor roles.

In the 108 hijacking attempts, 70 involved the use of real firearms, nearly all of which were handguns, although there were several instances of shotguns and rifles which were assembled on the aircraft.

Twenty-five cases involved the use of a cutting weapon such as a knife, razor, or, in one case, a hatchet. In 15 of these cases, threats were made without the use of a gun, but sometimes there was a bomb threat. In the remaining ten cases, cutting weapons were supplementary to guns. Of a total of 31 bomb or grenade threats, five were identified as backed up by real weapons. In nine cases, a bomb or grenade was indicated as the sole weapon. In two cases, no weapon was shown or implied, but in one of these the hijacker threatened to set the aircraft afire.

In four cases of the 108, the hijackers signified their intentions before boarding the aircraft, using weapons to gain entry. In one case a hostage bus driver was taken aboard. In most of the other cases, the hijackers purchased tickets, but there were some special circumstances worth noting. Four hijackings involved the transfer of escorted prisoners who did not purchase their own tickets, and three involved military personnel traveling on government travel requests.

Twelve hijackers had no detectable weapons.

In addition to hijackings, there have been a very large number of telephoned bomb threats to airport terminals. All proved to be hoaxes, but they resulted in some disruption of service.

D. PRESENT ANTI-HIJACK PROCEDURES

The FAA-developed "Gate Plan" and "Airport Plan" are the bases for current anti-hijacking efforts. These plans describe procedures for preventing and deterring hijack and sabotage attempts by screening passengers before they board an airplane. The essential elements of both plans are:

- The application of the "hijacker behavioral profile"; the interview (identification of individuals selected by the profile test).
- The use of metal detectors.
- Search of luggage and persons.

In the Gate Plan there is a metal detector at each gate, while in the Airport Plan metal detectors are shared among several gates. In the Gate Plan, all passengers walk through a metal detector, but identification usually is required only of those who show evidence of metal and who also match the profile. In the Airport Plan, the metal detector is used only on those individuals who cannot produce satisfactory identification. If a metal detector is not available, the metal detector procedure is simply omitted. The carriers have the right to refuse passage at any time to an individual they consider to be threatening or disorderly. A further description of present procedures will be found in the companion report (Ref. 2).

E. OPERATIONAL CONSTRAINTS

Several operational constraints hamper effective detection procedures. Passenger delay and inconvenience are most often cited. Hijackers number about one in every ten million passengers. The passengers (up to 350 for a 747) have to be boarded in a period of 10 to 15 minutes. The preferred screening procedures are those that entail the least boarding delay and that do not inconvenience, irritate, or interfere with the privacy of the passenger. Obviously, complete baggage search and frisking of passengers would prevent the boarding of conventional weapons and explosives. There could be a requirement for the display of all metallic articles carried by passengers, and the lack of metal could be confirmed by sensitive metal detectors. Such procedures are cumbersome and irksome (but essentially these procedures are employed by some foreign international carriers). As reported in Ref. 2, vigilance is a major problem. The safety of screening procedures (such as X-radiation) is also a significant consideration.

F. CAVEATS

It should be noted that several subjects are either not addressed or are given only passing attention in this report. Our treatment of weapons detection is limited to metallic weapons and does not cover exotic ones made of plastic or similar materials. We do not examine the public acceptability of the various techniques discussed because this paper is concerned primarily with technical feasibility. We do not attempt a detailed operational evaluation of the devices which appear technically feasible. And, finally, we do not undertake a thorough cost (or cost-benefit) analysis. Rough guides to costs are included, where known, but these have not been investigated in depth.

II. NONIMAGING TECHNIQUES

A. PHYSIOLOGICAL OBSERVATION

One of the frequently suggested techniques for detection of potential hijackers is by observation of their physical and emotional state. The hypothesis is that prospective hijackers will display characteristics different from the normal passenger. There is little to support this contention.

In our previous study on the protection of public figures (Ref. 1), it was concluded that: "The detection of potential assassins by remote sensing of stress indicators ... has been considered as a possibility. No prospects are offered for its use at present." There has been little change in this situation in the intervening years, although some new instruments are available. The difficulties of calibrating and interpreting physiological measurements and relating them to an intent to hijack are formidable if not impossible. Even the development of an operationally useful warning signal is beyond the present state of the art. (See, for example, Ref. 3.)

Emotional reactions are accompanied by physiological responses. These latter may be changes in blood pressure, pulse rate, voice frequencies, vasomotor dilation or contraction (i.e., blushing or blanching of the face) sweat rate, rate and depth of respiration, salivation, pupillary aperture, goose pimples, and others. The problem of measuring these changes accurately and, if necessary, covertly, limits their usefulness in a screening process as indicators of emotional response to stress. A few physiological changes lend themselves to measurement by accurate remote sensing devices. Among these are skin temperature as a function of blood flow, pulse rate,

galvanic skin resistance as a function of sweating, and possibly a loss of subaudible voice frequencies (8-14 Hz).

To utilize such measurements, frisking by a U.S. marshal (prompted by an alert from another screen) might be accompanied by a period of questioning utilizing a series of control questions and positive-response questions to evoke emotional responses. This would be a modification of the lie-detection technique in an informal but nonetheless controlled interrogation procedure. During the questioning period, certain of these physiological responses could then be monitored by remote sensing devices. The chair in which the subject sat could have a built-in cardiotachometer which would record changes in pulse rate in response to all questions with attention directed to certain key questions (Ref. 4). In addition, remote sensing of the face by infrared devices would record changes in the blood flow, which are a function of the vasomotor tone, which is a function of the emotional stress response.

Remote infrared sensing devices have been developed by Philco-Ford Corporation (Ref. 5), Honeywell Corporation (Ref. 6), Garrett Airesearch (Ref. 7), and Barnes Engineering. Unobtrusive cardiotachometers would be very simple to design and develop. They would consist of a sensitive diaphragm device embedded in the seat cushion. The rate and amplitude of change could be transmitted to the recording polygraph by telemetering or by tubing. In the latter case, the chair would have to be fixed to the floor but directly against a wall so that the tube could run unobserved through the wall into the recording chamber. In the recording chamber an operator would be seated at a polygraph recording console, which would record the infrared sensor as well as the cardiotachometer readings on a moving drum or sheet. Signals from a timing device would be recorded simultaneously. The operator would press a key to note the question asked and the time of the answer. Thus, the same moving record would show time of response and physiological changes. The operator would be trained in interpretation of the records and would tell the marshal whether the subject appeared to be deceptive about denying his intent to hijack the airplane.

However, the method suggested by this scenario is neither realistic nor effective. The value of developing any of these remote sensing devices is highly questionable, since without the control period and individual questioning by the marshal they would not give sufficient valid indications to justify their use. Further, stress symptoms are not restricted to potential hijackers. Outdoor temperature (hot or cold weather) will alter the motor tone of the blood vessels and affect the infrared responses independently of the subject's emotional state. Tobacco smoking will cause a contraction of the blood vessels independent of emotional state and serve to confuse the findings. The subject's pulse rate can be up if he has run to catch the airplane or if he has been carrying a heavy suitcase for a distance. Some people will respond in an overemotional way to any sort of police intervention, and their anxiety responses will give an impression of emotion that is totally unrelated to the intended crime of hijacking.

Another interrogation system recently proposed (Ref. 8) involves observation and human interpretation of the amplitudes of the various frequencies of the human voice. The procedure involves tape recording the passenger's voice for a few seconds and thereafter interpreting a paper trace recording of the processed voice signal. It is contended that under conditions of stress small muscle tensions develop, causing a detectable reduction of the voice waves produced in the infrasonic, subaudible frequency range (from 8 to 14 Hz). At present, the interpretation of the processed signal* is done by an operator. Complete and reliable information on the characteristics, concept of operation, and capabilities of this system is unavailable. Some carefully supervised, controlled experiments are necessary before any serious consideration of this technique is warranted.

B. DOGS AS SENSORS

It is well known that animals are capable of remarkable feats in the detection of very small quantities of specific materials in the

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*Processing characteristics are unknown.

atmosphere. Dogs have a highly developed sense of smell. It has been demonstrated that it is feasible to train dogs to detect explosives (e.g., Ref. 9), and it may even be possible to train them to detect concealed weapons. Dogs have acute visual, auditory, and odor perception. It has been roughly estimated (Ref. 10) that a trained dog can detect the presence of dynamite when it, or its distinctive effluent, is present in one part in 10^{12}. The success of operant-conditioned dogs to detect marijuana, mines, weapons, tunnels, and ambushes under field conditions is one reason for continued study of vapor emission analysis technology (Section II-E). It is contended that if a dog can detect explosives, something measurable must be present.

Recent trials (September-October 1971) at the John F. Kennedy International Airport indicated the capability of dogs to find specimens of TNT and black powder in an airport environment. Small quantities of these materials were secreted in various areas of the airport terminal, including public passenger ticketing areas, baggage handling and storage areas and various types of aircraft in all stages of use from hangared, unattended aircraft under repair to those in final preparation for flight, and in the final boarding process. In the words of the memorandum report (Ref. 9):

> "The dogs performed well and improved markedly, from a shaky nervous beginning to an assured acceptance and adaptability to aircraft and airport environment. They located each specimen quickly, were not distracted by the many noises and odors of airport activity and proved themselves to be a valuable tool or aid in the detection of this type of sabotage or threat to aircraft and airport security.
>
> "In addition to proving the feasibility of the use of these trained animals, additional training and improved expertise was gained by the handlers and security forces involved in the program."

The consistency of the dogs in the foregoing trials was sometimes doubtful. Further, the full significance of the trials is somewhat

suspect because the number of plants to be found was known to the handlers. More carefully controlled trials are warranted to determine the limits of dogs' capability.

The United Kingdom has reported that the use of dogs to detect explosives appears as a promising technique, inasmuch as success has been achieved with their use in detecting drugs. Because the use of dogs in the area of explosives detection is fairly new, much work needs to be done in evaluating their effectiveness, and a series of trials is being undertaken to assess quantitatively the performance and reliability of dogs in this role. Preliminary tests with dogs have been promising, and a program in the United Kingdom will evaluate this technique in depth.

Advantages of dogs as detection sensors are low cost, low logistic support requirements, silent and flexible operation, and the inherent deterrent effect drawn from a public belief (perhaps unwarranted) in the extreme effectiveness of the animals. Dogs can enter and search areas difficult for men to get into. Search dogs could reduce the total manpower requirement of an all-human inspection system.

A serious disadvantage of the use of dogs is their need for a trained handler. Further limitations of dogs as detectors are all the vulnerabilities of living things: disease, injury, and fatigue. Search dogs, as is the case for any trained animal, must be kept healthy and exercised. Initial training requires several months. Some periodic retraining is necessary, as much for the handlers as the dogs. Distractions (e.g., other dogs, rodents, food) can seriously degrade capabilities. Skillful handling is the single most important factor in the successful employment of search dogs.

In sum, dogs have a capability of finding at least some explosive devices, but much remains to be learned about this capability. A controlled experiment with one or two dozen dogs would seem warranted at this time. It is estimated that an experimental program designed

to determine the limits of dogs' capabilities as detectors could be performed over a period of three or four months for less than $100,000. Thereafter, if some success has been achieved, investigation could be undertaken to evaluate preferred dog training programs.

C. MASS DETECTION

The presence of handguns, grenades, and perhaps other explosives could, in concept, be indicated by observation of a distinctive distribution of mass, either on the person or in handbags or baggage.

For baggage inspection possible measurable quantities include weight; center of gravity; length, width, and height; rotational acceleration. Volume, density and moment of inertia can be calculated (about several axes for bags).

Average density of a bag might be used as a measure. The only justification for the use of this technique rests on the hypothesis that baggage that is abnormally light or heavy is more likely to contain explosives. By the light criterion, the nearly empty bag containing only a small weight (say, four sticks of dynamite and a firing mechanism) might be detected; by the heavy criterion, a bag full of explosives might be signaled. Admittedly, *a priori*, these possibilities are very remote. There are just too many variations in the normal contents of baggage and in packing. The technique cannot be regarded seriously unless sufficient measurements are made of weight and related mass distribution of ordinary luggage to establish the plausibility that objects such as guns and explosives might be detected by measuring mass distribution.

For concealed handgun detection, the different responses of various parts of the body to low-frequency vibration (i.e., on a 1- to 3-Hz shake table) could conceivably be used to locate an anomalous concentration of mass. Again, the wide range of manner and place of concealment and of covering clothing makes this technique implausible.

D. MICROWAVE AND MILLIMETER-WAVE TECHNIQUES

1. Radar

It has been suggested that the radar cross section of weapons obtained at an appropriate microwave frequency, or at selected frequency combinations, or with variable polarization, may produce returns which are distinguishable from the backscatter of the body or of objects normally worn or carried. There is no analysis or experimental evidence to support this contention, and there is no reason to support research on detection of concealed weapons by this means. A more detailed discussion of the problems inherent in this technique is given in Section II-C of IDA Study S-332 (Ref. 1), and the state of the art remains unchanged.

2. Radiometry

Radiometry is the passive detection of signals of thermal origin. The thermal signals from a body arise from two sources: (a) the thermal emission of the body itself, which is determined by the body's temperature and emissivity; and (b) the radiation from other thermal emitters (such as the sun and the earth) which the body scatters. Radiometry in the infrared region of the spectrum has had extensive development. Microwave and millimeter-wave radiometry have had lesser development efforts, though a considerable amount of research has been done at these frequencies. An excellent summary of this work is available in the review article by King (Ref. 11). This discussion will concentrate upon problems in the detection of concealed weapons with microwave and millimeter-wave radiometry, and the reader is referred to King's article and references for a discussion of the basic principles.

At millimeter (and longer) wavelengths, the value of $h\nu/kT$ is small. For example, $h\nu/kT = 10^{-2}$ at $\nu = 60$ GHz. For these wavelengths the Rayleigh-Jeans approximation of the Planck radiation law is valid, so that the radiation emitted by a body is proportional to kT. The total power received from a body can be separated into two components: (1) the radiation emitted by the body and (2) the background radiation

scattered by the body. At millimeter wavelengths these components can be expressed linearly in terms of temperatures which have the following relationship:

$$T_a = \epsilon T_o + AT_b$$

where

T_a = apparent temperature of the body
ϵ = emissivity of the body
T_o = physical temperature of the body
T_b = apparent temperature of the background
A = albedo

For surfaces so thick that no incident radiation is transmitted, $A = 1-\epsilon$ and $T_a = \epsilon T_o + (1-\epsilon) T_b$. For a blackbody ϵ equals one, and for a perfect reflector ϵ is zero. Metals are nearly perfect reflectors, so that the apparent temperature of a metal equals T_b, the apparent temperature of the background. Most common vegetation and surface materials have emissivities of about 0.9, and water, with $\epsilon \sim 0.4$, is intermediate in emissivity between these materials and metals.

The apparent temperature of the clear sky at zenith is very low (85^{o}K), as seen from the dashed curve of Fig. 1 (Ref. 12). The presence of clouds, however, can cause significant changes in sky temperature. Changes of 20^{o}K can occur within 10 seconds, and a variation of 85^{o}K was observed during the 15-minute observation time. If a metal object is arranged so that it receives illumination primarily from the sky, then its apparent temperature will duplicate the variations in sky temperature which occur. Materials which have higher emissivities will be less affected, since the sky temperature modifies the physical temperature in the ratio $(1-\epsilon)/\epsilon$.

A second factor which affects the apparent temperature of a metal object is its orientation. This is illustrated in Fig. 2, which is taken from an unpublished report by Space-General Corporation. The apparent temperature of a metal plate changed by 200^{o}K as the plate was

rotated from horizontal to vertical. The variation of temperature with angle was especially rapid within 45 deg of the vertical. The upper of the two curves marked 94 Gc in Fig. 2 apparently shows the effect of clouds, though this is not explicitly stated. The effect is similar to that shown in Fig. 1.

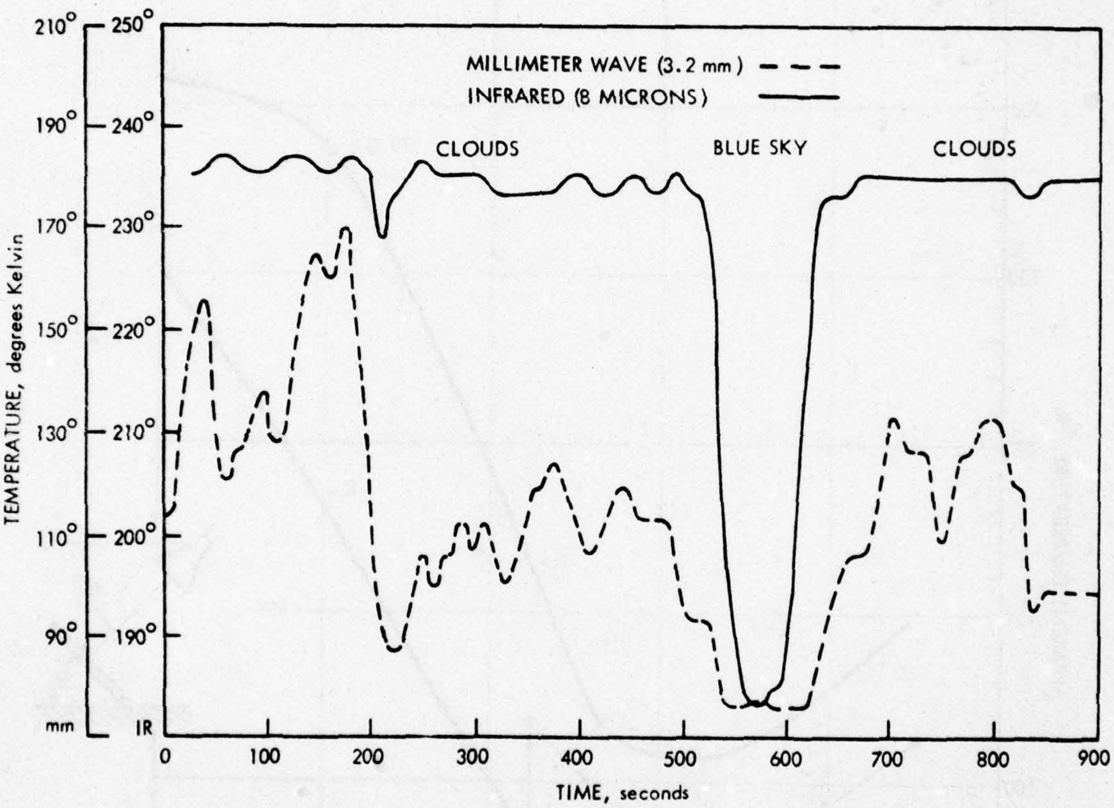


FIGURE 1. Experimental Zenith Sky Temperature Measured with Millimeter-Wave and Infrared Radiometers (Ref. 12)

The report by Space-General Corporation also included measurements of the apparent temperatures of horizontal surfaces of several materials. Asphalt, soil, and vegetation had an apparent temperature of 270°K, as would be expected for surfaces at a physical temperature of 300°K and an emissivity of about 0.9 with a background temperature of 85°K. The apparent temperature of a metal plate was 85°K, in

agreement with the results of Fig. 1. The apparent temperature of water was about 100°K, and water was the only material whose apparent temperature exhibited a very strong dependence upon polarization.

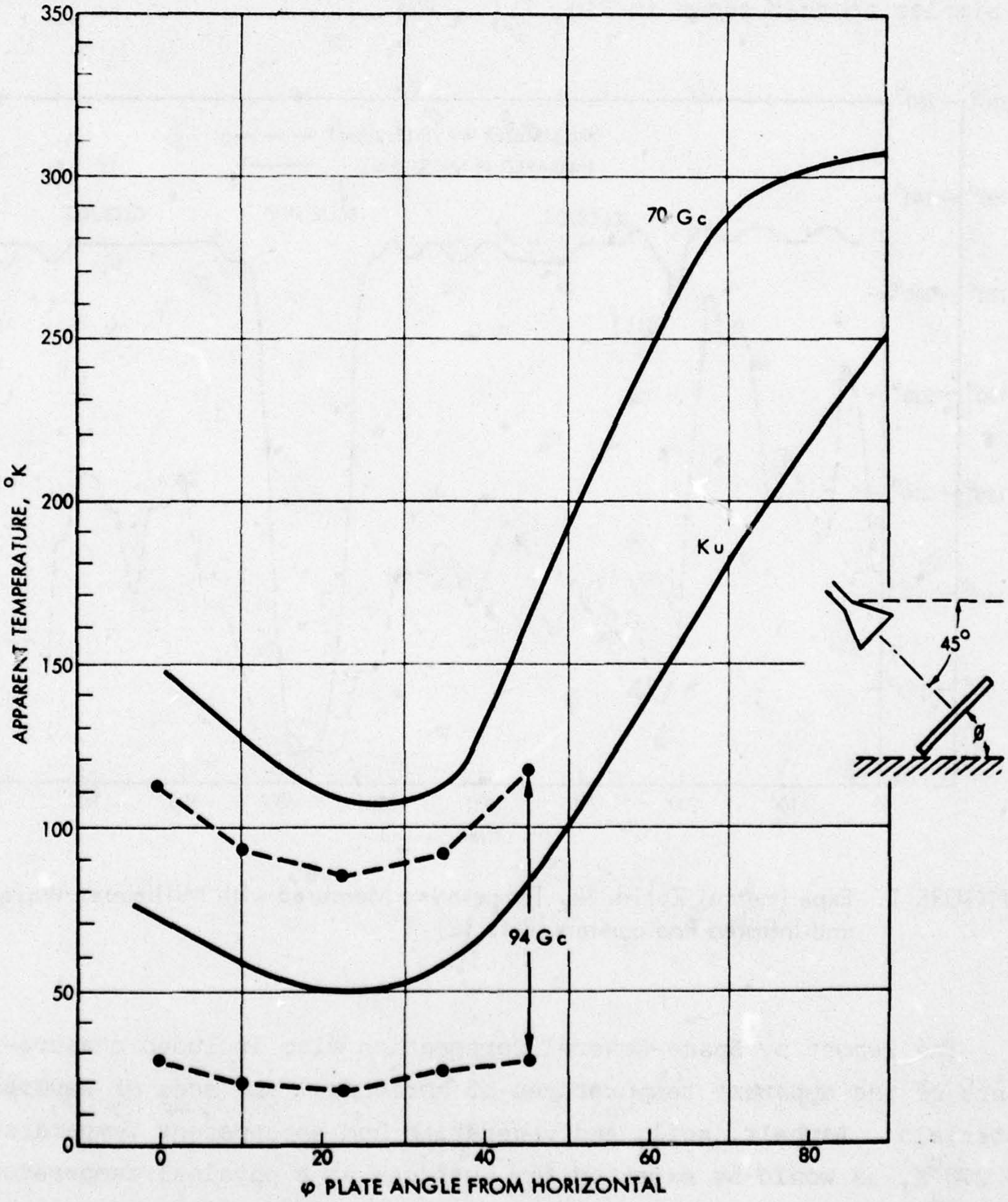


FIGURE 2. Temperature of the Metal Plate as a Function of Angle from the Horizontal (Courtesy of Space-General Corp.)

The apparent temperature of a person will depend upon his temperature, emissivity, and orientation, the temperature of the background, and the degree to which he fills the beam of the radiometer antenna. For an antenna which is not focused in the near field, the minimum beamwidth is the antenna diameter, which is characteristically about 1 ft or less at millimeter wavelengths. For an antenna diameter of 1 ft at a frequency of 30 GHz, the near field extends 30 ft from the antenna and so encompasses useful ranges for weapon detection. Throughout this range the beam will be 1 ft in diameter. The contrast of an object with the background will depend upon the difference in apparent temperatures of object and background, the uniformity of the background, and the extent to which the object fills the beam. The less the beam area occupied by the object, the greater the difference in object and background temperatures required to obtain a distinguishable signal. A handgun characteristically might occupy about 10 percent of the beam area, and so the observed contrast of the gun will be about 10 percent of the difference in apparent temperatures of gun and background. If the handgun reflects the sky at $85^{\circ}K$, and if the gun background is above $200^{\circ}K$, the observed temperature difference will be in excess of $10^{\circ}K$. Since radiometer sensitivities of $1^{\circ}K$ are readily obtainable, this difference is easily observable. However, if the background due to the body is determined primarily by its water content, its temperature might be as low as $100^{\circ}K$, resulting in a temperature difference of $1.5^{\circ}K$. This difference, though detectable, could be easily obscured by background and object temperature variations.

A further obstacle to the detection of concealed handguns is the normal presence of metal carried on the person or in pocketbooks. Cigarette cases and lighters, compacts, watchbands, keys, and even the foil on cigarette packs provide clutter objects which can be mistaken for weapons. These objects will generally be indistinguishable from guns.

Spectran, Inc. (Ref. 13) has studied the radiometric detection of concealed weapons under contract to the U.S. Army Mobility Equipment

Research and Development Center (MERDC) at Ft. Belvoir, Virginia. Radiometers at 10.2 and 30.0 GHz were employed, with antenna diameters of 1.5 ft and 1.0 ft, respectively. A large plywood board covered with aluminum foil tilted at approximately 45 deg to the vertical was used to reflect the zenith sky from individuals who served as subjects for measurement. Other radiation from the surroundings was also reflected from the individuals, but the sky radiation was expected to be dominant. This expectation was borne out by the fact that the measured body temperatures were consistently cooler than the background temperature of the surroundings.

Measurement of the apparent temperature of various parts of the body were made for six men and two women at horizontal and vertical polarization at both frequencies. Radiometric temperatures were measured of the knee, thigh, pelvis, abdomen, chest, neck, and face. The orientation of the body to the radiometer was very critical, as was the relative amount of skin surface moisture due to perspiration. Repetitive measurements were therefore highly variable. In addition, the temperature variation across the body was quite large. The chest, abdomen, and pelvis were generally, though not always, cooler than the knee, thigh, face, and neck. Table 2 shows some of the differences observed for various subjects. They are quite large. For a given portion of the anatomy the temperature also varied widely for the different subjects measured. Table 3 illustrates this. The wide variations of Table 2 and Table 3 show that individuals do not have a uniform radiometric temperature nor do specific portions of the anatomy. The body background is therefore highly variable and cannot be calibrated.

Temperature measurements were then made of portions of the body with and without metal objects. The results were inconclusive. Metal usually gave a colder reading than the body alone, but the magnitude was not always consistent with the size of the metal. In light of the normal body temperature variations, the differential temperature with metal present was not a consistently distinguishable signal. The magnitude of the differential was so small that it was unlikely to be

TABLE 2. RADIOMETRIC BODY TEMPERATURES*

Frequency, GHz	Polarization	Part I	Part II	Temperature, °K* Part I	Part II
30	Horizontal	Thigh	Chest	2.5	71.0
30	Horizontal	Thigh	Chest	3.4	59.9
30	Vertical	Face	Abdomen	6.5	43.5
10	Horizontal	Neck	Abdomen	15.6	39.6
10	Vertical	Knee	Chest	1.4	49.4
10	Vertical	Thigh	Pelvis	3.1	39.3
10	Vertical	Thigh	Pelvis	8.0	8.1

*Temperatures are measured relative to the background and are cooler than the background

TABLE 3. SELECTED RADIOMETRIC TEMPERATURE VARIATIONS AMONG EIGHT SUBJECTS*

Frequency, GHz	Polarization	Body Part	Observed Temperature, °K Min.	Max.
10	Vertical	Thigh	2.4	11.2
10	Horizontal	Pelvis	10.7	48.0
30	Horizontal	Abdomen	24.0	53.7
30	Vertical	Chest	62.5	82.0
30	Vertical	Abdomen	28.5	63.0

*Temperatures are measured relative to the background and are cooler than the background.

noted. When the aluminum reflector was not used to reflect the zenith sky, the differential temperatures were even smaller.

The variations in background temperature, the uncertainty in signal strength due to variable illumination conditions and to weapon orientation, and the normal presence of metallic clutter objects preclude the use of microwave and millimeter-wave radiometry for the detection of concealed weapons.

3. Radar-Radiometry Combination

Neither nonimaging radar alone nor millimeter-wave radiometry alone appears useful in the detection of concealed weapons. A combination of the two may provide satisfactory target discrimination. Such utilization has been suggested in a different application by Foiani and Pearce (Ref. 14). They developed a system at 94 GHz to discriminate vehicles from the background of terrain and buildings. The system determines the radar scattering cross section and the apparent radiometric temperature of objects in the beam. Their results are shown in Fig. 3. The background objects fall within the dashed area of the temperature-versus-cross-section plot, whereas metallic objects fall well outside this area. Interestingly, neither temperature alone nor cross section alone provides this unambiguous separation.

Possibly a system of this kind might provide a useful distinction between metal objects and the body, and it might be of some help in discriminating against metallic clutter. A modest measurement program oriented to the detection of concealed weapons would be warranted at a laboratory where the necessary equipment is already available.

4. High Range Resolution Radar

One novel type of radar employs a wide bandwidth capability in measuring the response from a scattering object with high range resolution. The bandwidth needs to be sufficiently wide to support a system range resolution comparable to or smaller than the dimensions of the object of interest, depending upon the object detail which is of importance. Wide bandwidth has been used in several ways to obtain

high resolution: radiation of a short pulse (Ref. 15), and transmission of a frequency modulated signal which permits the determination of range from the frequency of the return (Refs. 16, 17). The possible application of such techniques to the detection of concealed weapons has been suggested by J.E. Bridges at IITRI. Alongi, Kell, and Newton (Ref. 16) have reported backscatter measurements at 9.95 GHz with range resolution of 3.0 inches (i.e., 2.5 wavelengths), and Foreman and Sedevic (Ref. 11) have performed such measurements at 2 GHz with pulse widths of 1 nanosecond (which contain only two cycles of the carrier frequency). Three-inch resolution might provide useful discrimination data in the backscatter from handguns, but resolution of one inch appears desirable, considering the possible variations in gun size and orientation. To obtain such resolution at 30 percent bandwidth would require a carrier frequency of 30 GHz.

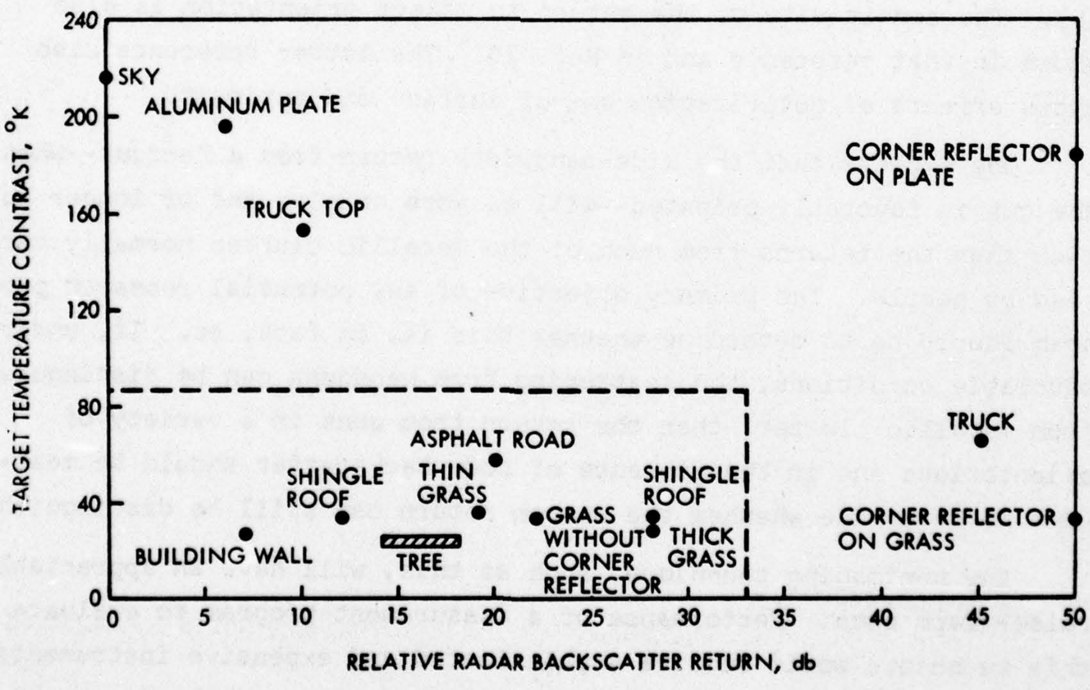


FIGURE 3. Radar and Radiometer Test Data (Ref. 14)

The state of the art in predicting the wide-bandwidth scattering for radar targets is primitive. It has been applied with some success to perfectly conducting targets of simple shape and to special orientations (Ref. 18). For example, the scattering of a pulse from a conducting sphere with a dielectric coating has been calculated by Rheinstein (Ref. 19). These calculations predict a specular return from the front of the object, travelling wave returns from discontinuities in curvature along the object surface, and a creeping wave return due to the diffraction of energy around the object and radiation back toward the source. The relative strengths of these components are highly sensitive to the object size, structure, and orientation and to the radiation wavelength, polarization, and resolution. The presence of all three components in the scattering from a sphere-capped cone has been demonstrated by Alongi, Kell, and Newton (Ref. 16). The sensitivity of the return to object orientation is also shown in that reference and in Ref. 15. The latter reference also shows effects of polarization and of surface discontinuity.

One expects that the wide-bandwidth return from a handgun--when the gun is favorably oriented--will be more complex and of longer duration than the returns from much of the metallic clutter normally carried by people. The primary objective of any potential research program should be to determine whether this is, in fact, so. If, under favorable conditions, the scattering from handguns can be distinguished from metallic clutter, then the return from guns in a variety of orientations and in the presence of body backscatter should be measured to determine whether the weapon return can still be distinguished.

Any nonimaging technique, such as this, will have an appreciable false-alarm rate. Performance of a measurement program to evaluate this technique would require sophisticated and expensive instrumentation, and any eventual operational equipment will undoubtedly be expensive. This technique suffers in comparison to other nonimaging techniques in that the detection of guns, if it proves possible, will require human observation of the signal and does not appear to be readily susceptible to automation. If appropriate test facilities are

available, then the small measurement program suggested above can be recommended. The technique is not of such promise to warrant the development of instrumentation or equipment specifically for its evaluation, however.

5. Conclusions

Neither nonimaging radar nor microwave or millimeter-wave radiometry alone appears promising for the detection of concealed weapons, but a combination of radar and radiometry might distinguish between metallic objects and the body and might help in discriminating against metallic clutter. A modest measurement program to test the capacities of such a radar-radiometric system would be in order if the necessary equipment is available.

High range resolution radar shows some promise for concealed weapons detection but a system of this kind would have a high false-alarm rate, would be expensive, and would be difficult to automate. Measurements to evaluate the technique would be justifiable only if they could be made without development of special equipment and instrumentation.

E. CHEMICAL DETECTION SYSTEMS

1. Introduction

Chemical or physical-chemical systems for the detection of firearms and explosives can be divided into two basic categories of vapor targets:

1. Natural vapors from material of potential hazard (e.g., vaporous exudates from explosives and gun oils, or powder-residue vapors from weapons).
2. Official marking materials. Principally, but not necessarily, overt measures wherein markers would be applied to weapons upon registration, to propellants, gun oils, cleaning solutions or explosives at manufacture, or to personnel following appropriate security screening or inspection.

In the earlier IDA study (Ref. 1) consideration was given to the possibilities for covert marking systems which might be applied to individuals or materials under close surveillance for whatever reason. This subject is not discussed further in this study. However, such possibilities do exist and are limited only by the restraints imposed by the operational situation and the imagination of the user.

Consideration has also been given to the possibilities for monitoring physiochemical emissions which might indicate some degree of potential personal instability and might be predictive of irrational acts. This hypothesis was disposed of then, and can be now, principally because of the lack of any known specific indicator of potential for violent acts, the nonspecificity of stress indicators, and the irrelevance of breath-alcohol measurement.

Two other important factors should be mentioned. First, many techniques can provide data of forensic value. Clearly, many detection schemes may also serve as identification measures and, as such, could be employed <u>ex post facto</u> as investigational aids or for trial evidence. A second consideration, relating mostly to chemical marking for detection purposes but also to some forms of natural emissions measurement, is the potential for spoofing, avoidance, or harassment operations. Thus, an informed troublemaker could avoid detection by utilizing unregistered weapons or unmarked supplies, while provocateurs could overload any system by sending or carrying, say, a handkerchief drenched in marking materials or compounds so close to natural-vapor materials in physical-chemical reactivity that alarm logic would be unable to distinguish the difference. Absolutely foolproof detection schemes are extremely rare, but this does not necessarily deny their usefulness.

In brief, the value of detecting or monitoring natural or marker emissions depends on the coupling of appropriately sensitive and specific detection apparatus for the sought-after chemical species or physical-chemical reaction with other means and procedures in the operational situation.

The following sections present a basic understanding of the signal characteristics and vapor analysis techniques. Neutron activation techniques are discussed in Section II-E-5.

2. Target Signal Characteristics

a. Firearms. Coatings of volatile chemical materials on firearms are unnecessary. Thus, schemes to detect such materials on firearms suffer when the materials are not present. Guns do not have to be oiled to function, nor need they be cleaned or tested in such a manner that propellant residues are unavoidably retained on their surfaces. This obvious operational disadvantage has reduced interest in research in this area. Today no devices are available for the detection of weapons by this method, and no studies to develop such a capability are known to be under way.

The two prime volatile materials that might be available from firearms are the hydrocarbon lubricating oils and cleaning solvents in the C_8 to C_{12} aliphatic hydrocarbon range, and the residual oxidized and unburnt propellant resulting from previous firings. Of these, the hydrocarbon oils and solvents are the better candidates for detection, not only because of the availability of several known means for establishing the presence of their vapors in air (e.g., flame photometry) but also because they are more volatile than firing residues.

Table 4 illustrates both the apparent attractiveness for designing sensor instrumentation for such materials, and the reason for the paucity of research proposals in this area. The second column of this table indicates the vapor concentration theoretically achievable in 10 minutes for the named hydrocarbons when exposed from a surface area comparable to that of a small handgun at a temperature approximating body temperature (actually slightly higher, $40^{\circ}C$ versus $37^{\circ}C$). As rugged and reliable gas chromatographs and other devices are available that could be designed specifically to detect these hydrocarbons at the 1-ppm level without difficulty, the possibilities for detecting handguns might appear promising.

TABLE 4. HYDROCARBON VAPOR PROPERTIES

Substance	10-Minute Concentration in 1000-ft^3 Chamber,* ppm	Vaporization Time,** minutes
n-octane	13.3	1.1
n-nonane	5.1	3.0
n-decane	2.1	7.3
n-undecane	1.4	10.7
n-duodecane	0.3	49.0

* Based upon vapor pressure at 40°C, substance homogeneously distributed, with 10-cm^2 surface exposed to 1-mph airstream.

** 50 mg distributed on 10-cm^2 surface in 1-mph airstream at 40°C.

The third column, however, lists the time required for vaporization of an amount of marker that would reasonably be expected to be applied to a hand weapons. Were the weapon drenched in these chemicals, the time to virtual extinction of signal would increase by a factor of 3 to 5 times, hardly providing enough time to make the trip from one's hotel to the airport in most metropolitan areas. Another discouraging observation would be that 50 mg of marker, if it could somehow be completely evaporated into a 1000-ft^3 chamber, would result in a maximum concentration of about 1.5 ppm. Thus, the figures in the second column should be limited to this level, regardless of their favorable volatility properties. Additionally, hydrocarbons of the type listed are normally present in areas close to fuel supplies, cleaning solvents, paints, inks, and those light lubricating oils used with toys, carriages, and small machines.

The detection of vapor-phase propellant residues is much more difficult. Here, the vapor pressures of potential signal chemicals are

more than four orders of magnitude lower than that of n-duodecane and are mostly on the inside of the gun barrel, which may be nestled in a holster under one or more layers of clothing.

The parameters that influence the potential for vapor-phase detection of small firearms, whether from a natural vapor or an added marker, depend on volatility and diffusivity of the indicator chemical. The indicator chemical must have sufficient volatility to produce a signal (vapor pressure ≥ 1 mm mercury), yet, as the potential area upon which it is likely to be applied is small, it cannot be too high (> 5 mm mercury) or the vaporization time for this molecular weight range will be so short (≤ 10 minutes) that the signal will become operationally meaningless. Examination of the values of these parameters suggests that no natural vapors are likely to be employable for vapor detection of handguns, and that it would be difficult to devise a "marker" suitable for the purpose. Further, the significant signal attenuation from diffusion of the indicator chemical from the weapon to the ambient air (from barrel or trigger mechanism past holster and clothing) has not been quantified.

In sum, vapor detection of firearms appears impossible by today's state of the art, and it is unlikely that additional R&D would improve the situation.

b. Explosives. Explosives detection is a different matter! Explosives can be detected by their vapors. This section will review this capability and will indicate other possibilities.

Table 5 lists the qualitative composition of the more common composite explosives. It is evident that the capability to detect TNT and RDX vapors would be sufficient to detect the presence of each of these composite explosives.

There remains, however, the need to detect other explosives, including black powder (EDNA) and nitroglycerin (NG), which are listed, with their elemental composition, in Table 6. It should be noted from this table that the reactive groupings of NO_2 and ONO_2 are common to all the compounds. This detection, either as parts of whole explosive

TABLE 5. COMPOSITE EXPLOSIVES, QUALITATIVE COMPOSITION

Name	Composition
Amatol	Ammonium Nitrate, TNT
Comp. A-3	RDX, Wax
Comp. B	RDX, TNT, Wax
Comp. C-4	RDX, Polyisobutylene
Cyclotol	RDX, TNT
HBX-O	RDX, TNT, Wax
Octol	HMX, TNT
Pentolite	PETN, TNT
Picratol	EXP. D, TNT
PTX-1	RDX, TETRYL, TNT
PTX-2	RDX, PETN, TNT

TABLE 6. MONOEXPLOSIVES

Code	Name	Elemental Composition
EDNA	Ethylene Dinitramine	$C_2H_6N_4O_4$
EXP. D	Ammonium Picrate	$C_6H_6N_4O_7$
HMX	Cyclotetramethylenetetranitramine	$C_4H_8N_8O_8$
NG	Nitroglycerin	$C_3H_5N_3O_9$
PETN	Pentaerythritol Tetranitrate	$C_5H_8N_4O_{12}$
Picric Acid	Picric Acid	$C_6H_3N_3O_7$
RDX	Cyclotrimethylenetrinitramine	$C_3H_6N_6O_6$
TETRYL	Trinitrophenylmethylnitramine	$C_7H_5N_5O_8$
TNETB	Trinitroethyl Trinitrobutyrate	$C_6H_6N_6O_{14}$
TNT	Trinitrotoluene	$C_7H_5N_3O_6$

molecules or as breakdown products, is the basis for some sensor instruments. Also, there is sufficient structural differentiation that detection schemes relying upon the complete molecules' properties are possible. In either case, detection is dependent upon the material's having a vapor-phase emission of sufficient intensity that the unavoidable environmental dilution will not result in concentrations lower than the detection capability of the instrumentation.

Table 7 was generated from data from quality control tests designed to evaluate environmental losses or instabilities that might be incurred by these materials upon prolonged storage. The amounts indicated from the vacuum stability test (described in the table) are an upper bound on the availability of volatile materials for detection purposes. Column 3 lists the amount of such signal material expected from 1 lb of each explosive, for the same surface-to-mass geometry as in the test. One pound was chosen as a reasonable lower limit for an effective device and as a convenient basis for calculating for larger masses.

Column 4 of Table 7 shows the maximum concentration of volatiles obtainable from 1 lb of explosive when the volatile materials are enclosed in a 1000-ft^3 chamber. The selection of a chamber measuring 10x10x10 ft was assumed to provide a reasonably sized batch-processing volume for luggage or packages. No allowance is made for sorption to surfaces of containers or to the chamber walls. As 48 hours of the vacuum stability test conditions are unlikely to be achieved for baggage or package inspection, the total vapor phase concentration expected if the equivalent of 10 sec of these conditions can be achieved is shown in Column 5.

Lack of adequate sensitivity was why vapor-phase detection of explosives was initially so difficult and also why dynamite (essentially an inert-absorbent saturated with NG and other additives) was the first explosive detected. An encouraging fact is that at least one production instrument (Hydronautics Explosives Detector) has demonstrated the detection of TNT, although its theoretical emissivity (Column 5) is as low as any of the listed monoexplosives.

TABLE 7. PROPERTIES OF MONOEXPLOSIVES

(1) Material	(2) Molecular Weight	(3) Volatile Emissivity Limit,* g/lb	(4) Concentration of (3) if Contained in 1000-ft^3 Chamber, ppm	(5) 10-Second Equivalent Concentration,** ppb
EDNA	150	0.57	17	0.10
EXP. D	246	3.69	112	0.65
HMX	296	0.59	18	0.10
NG	227	> 50.51	> 1529	8.85
PETN	316	1.33	40	0.23
Picric Acid	229	0.46	14	0.08
RDX	222	0.44	13	0.08
TETRYL	287	1.29	39	0.23
TNETB	386	4.67	141	0.82
TNT	227	0.45	14	0.08

* From vacuum stability tests which measure the total volume of gases evolved during 48-hr exposure to vacuum at 100°C.

** For linearity of vapor emission as a function of time, 10x10x10-ft chamber, and maintenance of emissivity conditions equivalent to 10 sec of those obtaining in the vacuum stability test (footnote above).

It is not known whether there is some unique reactive property of the TNT molecule (or another simultaneously occurring contaminant or breakdown material) which permits detection at this level that is not present in EDNA, HMX, picric acid, or RDX. It is our estimate however, that this is not the case and that optimization of the detection apparatus will also, in time, permit detection of these explosives.

Other aspects of the detection problem are not so favorable. Table 7 omits all consideration of the cumulative effect of operational (environmental) factors which seriously degrade vapor-phase detection possibilities. Foremost among these would be the manner of packaging the explosives and the achievable ambient temperature and pressure differentials. The present state of the art for "sniffer-type" detection progressively declines from the parts-per-million level for field instruments for some common materials to approximately 0.05 parts per billion (ppb) for a very few materials under carefully selected conditions. Thus, any depression of achievable emissivity would take ambient concentrations below the threshold of detection. Another consideration is that the effluent available can be reduced by wrapping the explosive in plastic or placing it in a Mason jar or tin can.

Hydronautics (Ref. 20) has demonstrated that surface sorption phenomena significantly influence ambient air concentration of TNT vapor emissions. Thus, polyethylene film briefly exposed to TNT retains detectable amounts of vapor for several weeks. Also, a small quantity (a few grams) exposed to the air in a room is detectable in the air in a few moments and remains detectable on the walls for several months, but when it is placed inside a suitcase, flexing or breathing is required to obtain the signal from outside the unopened case. As this manipulation is easily accomplished by several means, it does not influence the operational usefulness of the instrument as a TNT detector for packages or suitcases. However, other explosives similarly enclosed in a package or suitcase might be impossible to detect, and that is operationally significant.

In brief, the volatility of explosives other than nitroglycerin or dynamite is not promising for purposes of detection. In fact, projected emissivity levels for many monoexplosives are so low that the detectability of 1-lb masses of these materials could be considered unlikely (i.e., achievable vapor concentrations below 1 ppb), were it not for the fait accompli of TNT detection. This single observation serves both to encourage the thought that similar detectors might be developed for the other explosives and to indicate caution in projecting development success, considering the long time interval from Dravnieks' (Ref. 21) first proposal (ca. 1963) to today's hardware.

3. Vapor-Emission Analysis Applications

The principal difficulty in achieving adequate, reliable, near real-time vapor-phase detection devices has been that in almost all cases the molecules sought comprise only an extremely small portion of the total number of molecules available for analysis. Further, in many cases the critical molecules are only subtly dissimilar to other molecules likely to be encountered. It is this case which seems to apply to the explosives and firearms problem.

As indicated in the earlier section, explosives detection by vapor-emission analysis is the more extensively researched. One partially field-evaluated advanced prototype instrument, three early prototype devices, and several laboratory instruments, some of which are described more completely below, are already in being.

Vapor-phase sensors are of two general types: (1) nitrogen detectors, limited by difficulties of discriminating signal from a measurable and variable background; and (2) organic molecule detectors, limited by the difficulty in detecting the low levels (parts per billion or less) of indicator chemical species.

In either case, it is highly desirable to separate from the bulk of ambient molecules that portion most likely to contain the desired species and to collect a sufficient quantity of this aliquot that, by

exploiting some reactive property or properties of the molecules, their separation into alarm and nonalarm portions becomes possible.

Thus, the procedure can be divided into four segments:

1. Selection-concentration
2. Separation
3. Measurement
4. Decision logic and signal presentation.

There are several possibilities for performing each of steps 2 and 3, such as gas chromatography, migration in an electric or magnetic field, flame emission or plasma discharge spectroscopy, thermal conductivity, electron capture, and absorption spectroscopy. The selection is principally dependent upon the product derived from step 1. The next section discusses gas analysis technology in greater detail. Decision logic and signal presentation are essentially reduced to circuit-board problems whose output need only be made compatible with the skills and situational problems of the operator.

In simple terms, all sensors require the delivery of a finite amount of material within a sufficiently short period of time in order to elicit a response greater than the electrical and/or ambient background noise inherent in the system. As indicated earlier, for the detection of explosives this mass must be obtained usually from dilutions of signal ranging from one part in 10^9 to one part in 10^{15} or greater. This immense range and uncertainty results from the fact that ambient vapor pressures of marker chemical species are all significantly less than 1 mm mercury, each marker species being subject to the influence of a wide variety of exposures to substances to which each marker has an unknown surface sorption-desorption index, and each such interaction being significantly influenced by small changes in ambient conditions (e.g., packaging and climate). The result is an inability to estimate reliably the likely signal concentrations under operational conditions. Even under laboratory conditions the generation and measurement of extremely dilute gas mixtures is a highly uncertain business. Under such conditions most successful instruments

today rely upon preconcentration of selected species or chemical exclusion of undesired species. Empirical evidence is collected to demonstrate operational capabilities.

For these reasons, the critical step is the first: selection-concentration. Many approaches have been tried, but the three which appear the most promising are:

1. Molecular exclusion of unwanted species, e.g., the use of semipermeable membranes on the Varian mass spectrometer.
2. Reaction-product measurement, e.g., the use of ion-molecule reactions to preselect species for analysis in the Franklin GNO plasma chromatrograph.
3. Selective sorption-desorption of desired molecules, e.g., the platinum wire sampling and bake-off device of the Hydronautics explosives detector.

The first two concepts are under development and may serve explosives detection requirements.

The third approach, the Hydronautics instrument, is undergoing evaluation of its detection potential for dynamite- and TNT-based explosives but has yet to be investigated for other monoexplosives. (It might also be used for drug detection.) Such a program should be undertaken.

Another possibility that merits consideration would be to mix and match the selector-concentrators listed above with other separator-measurers described in more detail below. It may well be that the combination of, say, the Hydronautics sampler module with IITRI's DC discharge emission analyzer and/or the plasma chromatograph would be synergistic. Other combinations and permutations should also be investigated.

Listed below with some pertinent information are the principal devices available for explosives detection in the summer of 1971, in approximate order of suitability:

Device	Principle	Status	Sponsor
Hydronautics, Inc. Explosives Detector	Sample concentration, gas chromatograph	Prototype production, operational testing	Gov't of Israel and Hydronautics, Inc.
Varian Associates Mass Spectrometer	Molecular exclusion sampling, mass spectrograph	Single prototype field testing	Land Warfare Lab. (LWL)
Franklin GNO Corp. Plasma Chromatograph	Ion-molecule interactions, and electrical field drift times	Single prototype field testing	LWL FAA ARPA
IITRI DC Discharge Emission Analyzer	DC discharge emission spectrograph	Lab prototype	MERDC
Research Planning Corp. Detector	Bioluminescent materials	Prototype test instrument	LWL FAA

The above listing is not all-inclusive but contains only those devices sufficiently advanced to permit realistic evaluation.

Some brief comments on the status of each of the five devices described above follow:

1. Hydronautics: Furthest developed, most promising device. Present configuration can detect TNT or dynamite. Has been partially field-tested in Israel. No interferences or false positive responses have occurred during two years of testing.

2. Varian Associates: Prototype unit has detected vapors from TNT-based explosives. More dilute signal strengths in laboratory tests introduce signal-to-noise problems. Potential interferences not fully evaluated. Somewhat slow response time.

3. Franklin GNO: Field experiences similar to Varian instrument above. Quick response, potential interferences not fully evaluated.

4. IITRI: Device has potentially the highest sensitivity, but reliance on nitrogen detection may introduce significant signal discrimination difficulties in field operation.

5. Research Planning Corp.: Detector makes use of an interesting phenomenon relying on the response of biological materials to trace gases; not yet evaluated under operational conditions.

Hopefully, this section has conveyed the active and dynamic nature of the vapor sensing field. While application to firearms detection does not appear promising, other devices for the detection of explosives have more than laboratory interest. With so many devices undergoing prototype or operational field test, changes in status could occur quickly. The following organizations are concerned with research and development in this area:

- U.S. Army Land Warfare Laboratory (LWL)
  Aberdeen Proving Ground
  Aberdeen, Maryland 21005

- Advanced Research Projects Agency (ARPA)
  Advanced Sensors Office
  1400 Wilson Blvd.
  Arlington, Virginia 22209

- Mobility Equipment Research and Development Center (MERDC)
  ID&S Laboratory
  Fort Belvoir, Virginia 22060

- Hydronautics, Inc.
  Pindell School Road
  Laurel, Maryland 20810

Other agencies, offices, and organizations are conducting mission-oriented tests and evaluations on instrument development. However, the above organizations have sufficient overlap of interest to encompass these programs.

4. Selected Advances in Gas Analysis Technology

The foregoing sections dealt primarily with some of the parameters influencing signal generation from weapons and explosives, and with those instruments developed to detect these signals. Gas analysis,

however, is limited neither to those target materials nor to those techniques. Other materials and other techniques should be included in any survey of "sniffing technology." The following is a selective survey of the subject of gas analysis, with several of the most dynamic technologies highlighted for future consideration. The technologies of gas chromatography and mass spectrometry are basic to some of the devices described in the previous section and are not further described here.

a. General Comparison of Techniques and New Instrument Development. At the outset let us discuss the detection limits for differing techniques of gas analysis. Table 8 compares several of the commonly employed techniques obtainable as off-the-shelf technology for industrial laboratories (Ref. 22). The table illustrates the wide range of sample sizes, thresholds, specifications, advantages and disadvantages of gas analysis methods. The detection thresholds are basically those of the instrument--if the sample to be analyzed is itself a concentrate, laboratory detection limits approximating one part in 10^{12} are achievable for almost every chemical of interest.

Table 9 is a representative listing of some of the new instrumentation displayed at one semiannual American Chemical Society meeting together with their costs and special features (Ref. 23). The table is an illustration of both the number of manufacturers and types of instrumentation available.

Several specific techniques for instrumented chemical analyses appear to be experiencing considerable R&D interest and a resultant improvement in both capability and reliability. These are discussed below.

b. Atomic Absorption Spectroscopy. Atomic absorption spectroscopy (AAS) measures the amount of ultraviolet or visible light of a specific wavelength (usually the resonance line) that is absorbed by ground-state atoms of an element. The resonance line is emitted by a lamp containing a cathode made from the element to be analyzed. The ground-state atoms in the vaporized sample absorb the resonance-line radiation

TABLE 8. COMPARISON OF GAS ANALYSIS METHODS (Ref. 22)

Method	Sample Size, cm^3	Detection Threshold, ppm	Comment
Atomic Absorption Spectrography	---*	0.001-0.2*	High specificity, limited range of elemental rather than molecular data. Sample requires extraction or desolution before analyses.
Mass Spectrometry	0.001-10	1-10	Small sample size requirement, good for separation of unknown gases and mixtures. Will not detect low concentrations of polar gases.
Gas Chromatography	0.1-20	0.01-10	High hydrocarbon sensitivity, easy repetitive analyses. Prior knowledge of qualitative composition requisite, limited range of materials per analyses.
Dispersive Infrared	≥ 100	0.05-100	High sensitivity for some gases. Must be IR-absorbing, large sample size required.
Flame Photometry	10-100	0.1	Continuous operation. Best for hydrocarbons.
Thermal Conductivity	10-100	1-50	Continuous operation. Limited to binary mixtures, unknown foreign gases can alter results.
Chemical Methods:			
Sulfur	100-1000	0.1	Specific.
Chloride	100-1000	0.1	Specific.

*Theoretical calculation assuming $\simeq$ 0.03-cm^3 gas volume dissolved in 10 ml of solvent.

TABLE 9. NEWLY DEVELOPED INSTRUMENTATION (Ref. 23)

Instrument	Manufacturer	Price	Features
Atomic Absorption/Emission Spectrophotometer (Model 353)	Instrumentation Laboratory, Inc. Lexington, Mass.	\$10,000	Dual channel and double beam, for simultaneous measurements of absorption and emission; second channel can be used as internal standard for enhanced precision; more than 400 analyses per hour with optimal automatic sampler; digital readout directly in concentration.
Atomic Absorption Spectrophotometer (Model 800)	Jarrell-Ash Division of Fisher Scientific Co. Waltham, Mass.	\$12,000	Two independent double-beam channels; one channel can be used for either absorption or flame emission; other channel can be used to determine a second metal or to compensate for changes in flame; digital readout as absorbance, per cent absorption, concentration, or emission intensity.
Electron Impact Spectrometer (ESCA 2.5)	McPherson Instrument Corp. Acton, Mass.	About \$50,000	Measures energies of electron transitions in gas atoms and molecules by impact with monoenergetic electron beam; spectrum of energy losses (-0.1 to 30 ev) identifies gas, and spectral density is proportional to concentration (100% to a few parts per million); for quantitative analysis, electron transition studies, air pollution studies, and identification of GC effluents.

(continued)

TABLE 9. (Continued)

Instrument	Manufacturer	Price	Features
Electron Spectrometer (ES100)	Picker Nuclear White Plains, N. Y.	$65,000 to $80,000	Double-focusing electron spectrometer to measure energies of electrons emitted from sample under X-ray bombardment; energy range from 100 to 4000 ev; applies to all elements from lithium up in mass; normally uses flat sample, typically 1 mm x 10 mm.
Portable Gas Chromatograph (Series 500)	Analytical Instrument Development, Inc. West Chester, Pa.	$ 2,750 to $ 2,900	For air and water sampling directly in the field, with sensitivity and resolution of laboratory gas chromatograph; weighs 22 lb, with rechargeable batteries and contained gas supply; four detector options; portable recorder, $810.
Gas Chromatograph (Model GC-M)	Beckman Instruments, Inc. Fullerton, Calif.	$ 2,975 to $ 4,150	For routine and student use; available in five versions (isothermal or programmed temperature, thermal conductivity or flame ionization detectors); two columns; choice of electrometers.
Gas Chromatograph (Pye Model R)	Philips Electronic Instruments Mt. Vernon, N. Y.	From $ 4,800	Modular design, including expandable oven, for expansion from routine analysis to research use; two columns and up to four ionization detectors in separate oven; optional pressure programming and Curie point pyrolyzer.

(continued)

TABLE 9. (Continued)

Instrument	Manufacturer	Price	Features
GC-IR System (Model 12-41)	Wilks Scientific Corp. South Norwalk, Conn.	$ 4,985	Heated transfer line couples any gas chromatograph to Model 41 vapor phase GC-IR analyzer and Model H-1200 infrared spectrophotometer for analysis of effluents with peak concentrations as low as 0.05 microliter per cc of carrier gas; variable scanning speeds from 1.5 to 20 min, oven range from 4000 to 650 cm^{-1}.
NMR Spectrometer (Model R-12A)	Perkin-Elmer Corp. Norwalk, Conn.	$20,000 to $30,000	Fluorine-19 capacity added to Model R-12; improved resolution and sensitivity; 50 and 100 Hz sweep ranges; total scan range 610 ppm.
Pyrolyzer (Pyrochrom Analyzer)	Chemical Data Systems, Inc. Oxford, Pa.	$ 7,500	Effluent from gas chromatograph is partially pyrolyzed by controlled thermolytic dissociation to give a characteristic and reproducible pattern of products when analyzed by a second chromatograph; unit also gives repeatable pyrolysis of volatiles for injection into single chromatograph.
Spectrophotometer with data processor (Spectronic System 400)	Bausch & Lomb Rochester, N. Y.	$ 3,640	Semiautomatic analysis of up to 400 samples per hr with Spectronic 100-8 spectrophotometer equipped with micro flow-thru sample compartment; DP-100 data processor prints absorbance, transmittance, or concentration, as well as controlling sample and purge cycle.

(continued)

TABLE 9. (Continued)

Instrument	Manufacturer	Price	Features
Differential Thermal Analyzer (Thermit 10-B)	T & T Technology, Inc. Madison, Wis.	About $ 2,000	Price includes potentiometric strip chart recorder; ambient to 1000°C; atmospheric or gas purge; closed-loop TC feedback with SCR proportional output power; optional modules for thermogravimetric and evolved gas analysis.
Thermal Analysis System (Thermoflex)	General Electric West Lynn, Mass.	$ 8,000 to $14,000	Compact, modular units for differential thermal analysis, thermogravimetric analysis, and derivative thermogravimetry; electric balance accurate to 10 micrograms; electric furnace with small heat capacity; temperatures to 1100°C.
X-Ray Diffractometer (Compak 2)	Siemens America, Inc. South Iselin, N. J.	$16,000	Low-cost, flexible horizontal diffractometer, with fail-safe safety devices; 4-kw power output from X-ray generator; scintillation detector, with pulse height analyzer, count-rate meter, and chart recorder; all solid state.
Vacuum X-Ray Quantometer (VXQ-72000)	Applied Research Laboratories Sunland, Calif.	$65,000 to $85,000	Simultaneous determination of as many as 23 elements, from fluorine through all heavier elements; suitable for on-line process control, with rapid analysis and simplified operation; computerizable digital output.

and cause a decrease in the intensity of the transmitted radiation. The change in incident radiation is detected and quantified by the instrument's photodetector. The outstanding advantage offered by AAS is its virtual immunity to spectral interferences. Sample preparations, therefore, can generally be confined to well-understood dissolution or extraction procedures (Ref. 24).

Table 10 gives the sensitivity of a representative AAS system based upon the mass of element required for 1 percent absorption (Ref. 25).

TABLE 10. REPRESENTATIVE AAS SENSITIVITIES IN GRAMS (Ref. 25)

Silver	2×10^{-11}	Potassium	2×10^{-11}
Aluminum	2×10^{-10}	Lithium	1×10^{-10}
Arsenic	1×10^{-8}	Magnesium	1×10^{-12}
Gold	5×10^{-11}	Manganese	2×10^{-11}
Beryllium	2×10^{-11}	Sodium	1×10^{-11}
Bismuth	2×10^{-10}	Nickel	1×10^{-9}
Calcium	1×10^{-10}	Lead	1×10^{-10}
Cadmium	1×10^{-12}	Palladium	5×10^{-10}
Cobalt	2×10^{-10}	Platinum	1×10^{-9}
Chromium	1×10^{-10}	Rubidium	5×10^{-11}
Cesium	1×10^{-10}	Antimony	1×10^{-9}
Copper	1×10^{-10}	Strontium	1×10^{-9}
Europium	1×10^{-7}	Thallium	1×10^{-10}
Iron	5×10^{-11}	Vanadium	3×10^{-9}
Mercury	2×10^{-8}	Zinc	2×10^{-12}

The extremely small quantities of material required for identification, even if the element is not applicable to explosives analyses per se, suggest the possibility of applicability to detection of volatile or microparticulate materials from firing residues (lead), initiators (mercury), or other accouterments of the firearms and explosives trade.

Table 11 indicates the detection limit for some elements obtainable from air samples of 1-ft^3 volume. In this table detection limits as defined are the smallest concentration producing a signal twice as large as the standard deviation of the base line (Ref. 26).

TABLE 11. ATMOSPHERIC AAS DETECTION LIMITS (Ref. 26)

Element	Concentration, mg/m^3
Aluminum	0.04
Arsenic	0.04
Beryllium	0.0004
Cadmium	0.0008
Cobalt	0.002
Copper	0.0008
Iron	0.002
Mercury	0.2
Magnesium	< 0.0001
Manganese	0.0008
Nickel	0.004
Lead	0.004
Selenium	0.04
Samarium	0.001
Tellurium	0.04
Zinc	0.0008

If one or more of the detectable elements can be unequivocally associated with a substance of interest, the parts-per-billion levels of detectability seem of potential operational significance.

c. Emission Spectroscopy. Basically, emission spectroscopy is the quantization of the characteristic radiant emission resulting from the return of an excited atom to its ground state. Only two varieties of excitation mechanisms are considered here, those occurring (a) in a separated, air-acetylene flame (Ref. 27) and (b) in an argon plasma (Ref. 28). The latter system was chosen because the high temperature (ca. 10,000^{o}K) argon plasma dissociates compounds that are normally considered refractory, and sufficient energy is available to excite atoms (e.g., chlorine) that are not usually suitable for spectrochemical analyses. Table 12 (Refs. 27, 28) shows the detection limits for several elements in each system.

TABLE 12. EMISSION SPECTROSCOPY DETECTION LIMITS, PARTS PER MILLION (Refs. 27, 28)

Element	Separated Flame	Argon Plasma
Silver	0.03	5.7
Barium	0.05	1.7
Calcium	0.002	16.9
Cadmium	1.5	4.2
Cobalt	0.04	8.4
Chromium	0.007	7.0
Copper	0.04	5.7
Iron	0.03	0.3
Magnesium	0.3	8.4
Manganese	0.01	16.9
Molybdenum	2.0	16.9
Nickel	0.05	1.7
Lead	0.5	0.6

The difference in detection limits of the two systems requires some explanation. The argon flame (in keeping with almost all other procedures discussed herein) actually is responsive to nanogram quantities of each element indicated; however, a standard integration time for the instrument evaluated is 15 seconds at a sample flow rate of 0.2 ml/minute--thus, for direct injection sampling of air, detection limits are essentially as shown. The point to be made is that it is the sensitivity of the total process which must be evaluated, not just the indicator reaction, and that changes in sampling injection volume, integration times, and preinjection concentration can significantly change operational detection limits.

The principal advantage offered by emission spectroscopy over AAS is that a reference electrode is not employed, which allows a wider range of simultaneous analytical capability to be engineered into each unit at the cost of slightly higher detection thresholds and potential background interference problems.

d. Ion-Selective Electrodes. Ion-selective membrane electrodes selectively measure the activities of unassociated ions in solution, with sensitivities often to less than one part per billion. All specific-ion electrodes consist of an insulating glass or plastic tube sealed across one end by a semipermeable membrane or solid-state ionic conductor. The tube usually contains a solution of the ion to be measured and an internal reference electrode. A voltmeter is employed to measure the potential developed between the specific-ion electrode and an external reference electrode when the pair is immersed in a solution. The specificity or selectivity of the system depends on the characteristics of the membrane. This membrane functions as a barrier, allowing only the desired ion to diffuse between the sample solution and the internal filling solution. The diffusion results from a difference in activity between the two solutions. When the activity of the ion in the sample exceeds that in the internal solution, there is a net diffusion of ions into the electrode. The transport of ions continues until a state of equilibrium is reached, at which point the electrical potential developed across the membrane prevents a further

net diffusion of ions. The value of the membrane potential at equilibrium E varies with the concentration of the ion in the sample. In practice, the electrode is calibrated with several solutions of known activity, so that measurement of E in an unknown solution gives the ion activity directly (Refs. 29, 30).

Table 13 lists some of the specific-ion electrodes now on the market and some of their characteristics (Ref. 29). A unique characteristic of such electrodes is that they sense ionic activity, which is often more meaningful than concentration, and yet they can also be made for direct reading in the more familiar analytical units of concentration (both free and total). In most cases electrode measurements are extremely rapid, often on the order of a fraction of a second, and can be continuous. The electrode is virtually nondestructive of the sample. Pretreatment of the sample solution is unnecessary in many cases. Direct measurements can be made on turbid and opaque solutions and even multiphase systems such as soil slurries. Thus, time-consuming separations such as filtration and distillation can be eliminated (Ref. 29).

The latter points have some importance, for these electrodes can only be used for solution studies. Therefore, studies of gas pollutants require provision for "scrubbing" with suitable reagents. Successful applications for monitoring sulfide, cyanide, fluoride, and hydrogen chloride are currently available as shelf items (Ref. 30). Of further advantage is that, compared to most other instrumental methods of analysis, the equipment required for ion-selective electrode studies is quite simple, easy to operate, relatively inexpensive, and adaptable to battery-operated modes of operation for field-study uses.

e. Laser Raman Spectroscopy. Primarily as a result of the development of reliable, high-power, continuously operating lasers, the field of Raman spectroscopy has increased greatly in activity in the last few years. Raman scattering is typically only some 10^{-6} the intensity of that employed for excitation, but its attractiveness for analytical purposes lies in the fact that the frequency of the emission

TABLE 13. SPECIFIC-ION ELECTRODES (Ref. 29)

Ion	Lower Detectable Limit, ppm	Principal Interferences
Bromide	0.4	CN^-, I^-, S^-
Cadmium	0.001	Ag^+, Hg^{++}, Cu^{++}, Fe^{++}, Pb^{++}
Calcium	0.4	Zn^{++}, Fe^{++}, Pb^{++}, Cu^{++}, Ni^{++}, Sr^{++}, Mg^{++}, Ba^{++}
Chloride	0.4	ClO_4^-, I^-, OH^-, NO_3^-, Br^-, OA_c^-, HCO_3^-, F^-, SO_4^-
Copper (II)	0.006	Ag^+, Hg^{++}, Fe^{+++}
Cyanide	0.3	S^-, I^-
Fluoride	0.02	OH^-
Fluoroborate	0.11	I^-, HCO_3^-, NO_3^-, F^-, Br^-, OA_c^-, OH^-, CI^-, SO_4
Iodide	0.007	S^-, CN^-, $S_2O_3^-$
Lead	0.02	Ag^+, Hg^{++}, Cu^{++}, Cd^{++}, Fe^{++}
Nitrate	0.6	ClO_4^-, I^-, ClO_3^-, S^-, Br^-, NO_2^-, CN^-, HCO_3
Perchlorate	1	OH^-, I^-, NO_3^-, MnO_4^-, IO_4^-, $Cr_2O_7^-$
Potassium	2	H^+, NH_4^+, Ag^+, Na^+, Li^+, Cs^+
Silver	0.01	Hg^{++}
Sodium	0.02	Ag^+, H^+, Li^+, K^+
Sulfide	0.003	
Thiocyanate	0.6	I^-, $S_2O_3^-$, Br^-, Cl^-, NH_3

is shifted from that of the excitation source by an amount characteristic of the substance illuminated (Ref. 31).

This so-called Raman shift is closely related to the infrared absorption frequency and most of the considerations that apply to interpreting IR spectra can be used, with some modification, in Raman spectroscopy (Ref. 32). By integration of high-powered lasers with specialized electronics and optics, it becomes possible to perform qualitative and quantitative analyses of remote species by using this technique. This development is a logical extension of LIDAR (Ref. 33), which utilizes the single-ended, remote, range-resolved measurement of light backscattered from particles to give a three-dimensional recording of their atmospheric concentration.

Table 14 illustrates sensitivities obtainable with either small, concentrated clouds or large, dilute ones under field conditions (Ref. 32). Quite low concentrations are detectable, particularly for such compounds as propane, hexane and organophosphates, and further suggest that the considerable improvements which might be possible under more controlled conditions (e.g., in the atmosphere of an aircraft baggage hold) where lower concentrations of potential interferences or background lumination might be obtainable, should be investigated.

5. Neutron Activation Analyses

When a chemical compound or a mixture of compounds is irradiated with neutrons, it becomes radioactive, and the energy, type, and half-life of the resulting radiation are characteristics of its elemental constituents. Further, the intensity of the radiation is proportional to the amounts of the elements present.

Since all common explosives contain a high proportion (by weight) of the element nitrogen, detection systems based upon the activation of this element have been investigated. All neutron activation techniques herein discussed are for the examination of packages or luggage, of course, and not people. These techniques would be useful only for detecting explosives, and not for detecting firearms or other weapons.

TABLE 14. REMOTE RAMAN DETECTION LIMITS AT 250 METERS (Ref. 32)

Compound	Concentration, ppm
Ammonia	1.8
Benzene	0.5
Butyl Alcohol	0.5
Carbon Dioxide	4.8
Carbon Monoxide	5.5
Chlorotrifluoromethane	1.5
Hexane	0.04
Hydrochloric Acid	2.2
Hydrogen	2.3
Hydrogen Sulfide	1.1
Methane	1.0
Phosphate Pesticide	0.02
Propane	0.05
Sulfur	1.7

A bomb detection system based on the $N^{14}(n,2n)N^{13}$ reaction is under development for the FAA by North American Rockwell (Ref. 34). In this system, irradiation of N^{14} by a 14-Mev neutron generator produces a radioactive N^{13}, which then decays to C^{13} by positron emission with a half-life of 10 minutes, and subsequent positron-electron annihilation produces two 0.511-Mev γ rays, which are the detection signal. Measurement of the intensity of such γ rays emitted by an irradiated package permits the amount of explosive in the package to be estimated. Approximately four sticks of dynamite or their nitrogen equivalent are required for unequivocal detection above background.

There are two sources of false alarms: (1) other nitrogen-rich materials such as leather and wool, and (2) sources of 0.511-Mev γ rays

other than nitrogen. The first can be minimized by accepting a "threshold" for detector activation. The second can be eliminated by measuring other parameters. For example, $O^{16}(n,p)N^{16}$ produces high-energy γ radiation followed by pair production and positron annihilation, but the short half-life (7.4 seconds) can be used to eliminate this reaction as a source of false alarms. The most troublesome sources of false alarms are the reactions $Cu^{63}(n,2n)Cu^{62}$ and $Al^{27}(n,p)Mg^{27}$, which have half-lives of 9.7 and 9.5 minutes, respectively. The Cu^{63} reaction produces positrons, but the slow neutron reactions with Cu^{64} and Cu^{66} can be used to avoid a false alarm from copper. The Al^{23} reaction produces a 0.842-Mev gamma whose tail would give some 0.511-Mev gammas. Measurements of the gamma peak at 0.842 Mev can prevent a false alarm from aluminum.

The principle has been demonstrated, and work is continuing on safety analyses and false-alarm studies. The radiation levels involved are low enough not to damage photographic film, and 30 minutes after irradiation induced activity of baggage has decayed to safe levels. Further measurements are needed to demonstrate that certain consumables (such as saccharin, vitamin B_1, and birth control pills) are not affected adversely.

This unavoidable activation of items consumable by humans introduces a serious obstacle to the ultimate feasibility of employing this or any other neutron activation concept. We can foresee that it may never be possible to prove, in the political sense, that induced radiation levels are "safe" at any measurable level, even though all calculated activations are several orders of magnitude smaller than the AEC permissible levels. Were this the case, perhaps a policy decision to ban the carrying of consumables through the network wherein the containers were likely to be irradiated would be the only solution.

Westinghouse Research Laboratories (Ref. 35), after conducting some preliminary studies, have proposed development of a system utilizing the $N^{14}(n,\gamma)N^{15}$ reaction. In this reaction, a low-energy or thermal neutron is employed to produce an excited N^{15} nucleus which

promptly returns to its stable ground state by the emission of gamma radiation. In 14 percent of these reactions this gamma radiation is of high energy (10.8 Mev), an event rarely encountered in other elemental neutron reactions. Apparent advantages of the Westinghouse system over the North American Rockwell system are its lower frequency of interfering reactions; higher counting rate response per gram of explosive at similar source-to-target distances; lower frequencies and intensities of nontarget material activations resulting from the use of lower energy neutron sources; and lower system costs resulting from the use of an isotopic neutron source (californium-252). Further experiments will be required to determine optimal cavity design, moderator material, and shielding requirements before any direct comparisons of the two techniques can be reliably made.

On balance, it seems clear that neutron activation could be employed to detect nitrogen-based explosives equivalent to three or four sticks of dynamite contained in a small package or luggage. The selection of the better system will be dependent upon engineering design, cost information, and operational test data not presently available. The use of such a system would, of course, depend upon reduction of the question of activation of consumables, mentioned earlier.

Both the North American Rockwell and Westinghouse neutron activation systems should be supported so that the remaining technical questions can be answered and a practical system engineered for possible deployment at baggage- and mail-handling facilities. The existence of a useful device could stimulate the requisite policy decisions for its effective employment.

6. Conclusions and Recommendations

- There are no chemical analysis systems presently available for the detection of firearms, nor are there any such concepts worthy of R&D support.

- TNT- or nitroglycerin-based explosives can be detected at close range by their vapor-phase emissions, provided that packaging techniques to reduce or eliminate these emissions are not

employed. The Hydronautics explosives detector is a purchasable item for this purpose. It is possible that similarly effective instrumentation could be developed for the detection of other explosives. Current R&D programs seem adequately directed toward these objectives and warrant only coordination by the FAA.

- Several methodologies for chemical analysis of trace materials appear promising for application to explosives detection. Their immediate utility is sufficiently remote, however, that no recommendation for FAA support is made at this time.
- It is highly likely that nitrogen-based explosives in luggage-sized containers can be detected by neutron activation techniques. A decision regarding the irradiation of consumables will likely be required before there can be general use of these techniques. More design and evaluation efforts on the North American Rockwell system and an alternative system proposed by Westinghouse are recommended.

F. METAL DETECTION

1. Introduction

The detection of sufficient metal to raise suspicion of the presence of a handgun is possible with a variety of existing magnetometers. In our earlier review (Ref. 1) we said:

> Magnetometer type devices, designed to detect the presence of material, suffer operationally from the large number of false alarms generated. However, the kinds of sensors developed for buried landmine detection and geophysical prospecting offer more promise. A portal detector combining, perhaps, both active and passive measurements would offer the prospect of false alarm rates below 10 percent.

As will be discussed briefly later, this projection has been validated.

The false-alarm rate can be minimized in two ways: (1) by limiting the nonvisible metallic objects a person may carry through an

inspection station, or (2) by improving the ability of magnetic detectors to recognize the magnetic signature of a weapon. As will be shown below in Section II-F-5, the magnetic field surrounding a metallic weapon contains more information than is commonly used. Much of this information is not measured in current metal detection systems designed for use in the prevention of hijacking.

A number of newer metallic weapon detection systems developed in the last few years have been and continue to be evaluated by the Transportation Systems Center (TSC) of the Department of Transportation (Ref. 36). This evaluation ranges from conventional passive magnetometers to measure perturbations of the earth's field to active systems with two frequencies, three orthogonal magnetic axes, and logic circuitry to discriminate between thick and thin metals and between ferrous and nonferrous metals.

2. Passive Magnetometers

Passive magnetometers are the most widely deployed. They are cheap, lightweight, and simple to install and operate. They respond to all magnetic materials, but their response is more dependent on prior history of the material than on its size, shape, and location. This can lead to both a low probability of detection and a high false-alarm rate. Weapons made of nonmagnetic materials are not detectable with these systems.

3. Active Metal Detection Systems

Active metal detection systems rely on induced currents produced by an alternating field of known and controllable frequency. This enhances the signature of objects examined, lowers the false-alarm rate, and permits detection of nonmagnetic metal objects.

Active metal detection instrumentation tends to be more expensive, larger in size and weight, and more difficult to adjust and operate. Active systems range in size from hand-held units for frisking individual passengers to walk-through tunnels for permanent or semipermanent installation. All active systems impose an alternating field on

the volume to be inspected and detect the effects of eddy currents induced in metallic objects. Frequencies used vary from 100 Hz to several hundred kilohertz, depending on the manufacturer. A variety of techniques are used to detect the presence of the induced eddy currents. In general, detection techniques can be divided into two categories: (1) those that use receiver coils to measure the induced fields and (2) those that measure reflected changes in the impedance or "Q" of the transmitter coils.

4. Recent Equipment Test Results

The tests of magnetic weapon detectors reported in Ref. 36 were limited in the number of trials under each set of experimental conditions, but this rapid preliminary survey was useful in demonstrating the complexity of testing magnetic weapons detectors and indicating the advantages and disadvantages of the different classes of detectors.

Additional measurements were made in the operational environment of Dulles International Airport with three systems representing three technologies of detection:

1. Multifrequency eddy-current absorption (Westinghouse)
2. Passive flux-gate magnetometer (Schonstedt)
3. Single-frequency unbalanced coil (Excelsior).

In the tests at Dulles, nearly 2000 volunteers were passed sequentially through all three systems under three conditions: (a) people only, (b) people plus purse or briefcase, and (c) people plus hand baggage. Some subjects were provided with weapons to carry through the detectors. The results are summarized below:

Test Condition	Westinghouse		Schonstedt		Excelsior	
	Detection Probability	False-Alarm Rate	Detection Probability	False-Alarm Rate	Detection Probability	False-Alarm Rate
People only	High*	5%	High*	25%	High*	55%
People + brief-case or purse	95%	65%	31%	50%	75%	75%
People + hand baggage	95%*	40%	80%*	80%	95%*	90%

*Sample size for people with weapons was too small to make anything but gross judgments.

For searching people, the goal of 90 percent detection probability with a 10 percent false-alarm rate is met by the Westinghouse system.

More recent trials at Dulles Airport with an improved Westinghouse system (adjusted to reflect the average amount of metallic articles carried on the person) produced the results shown in Fig. 4 (Ref. 37).

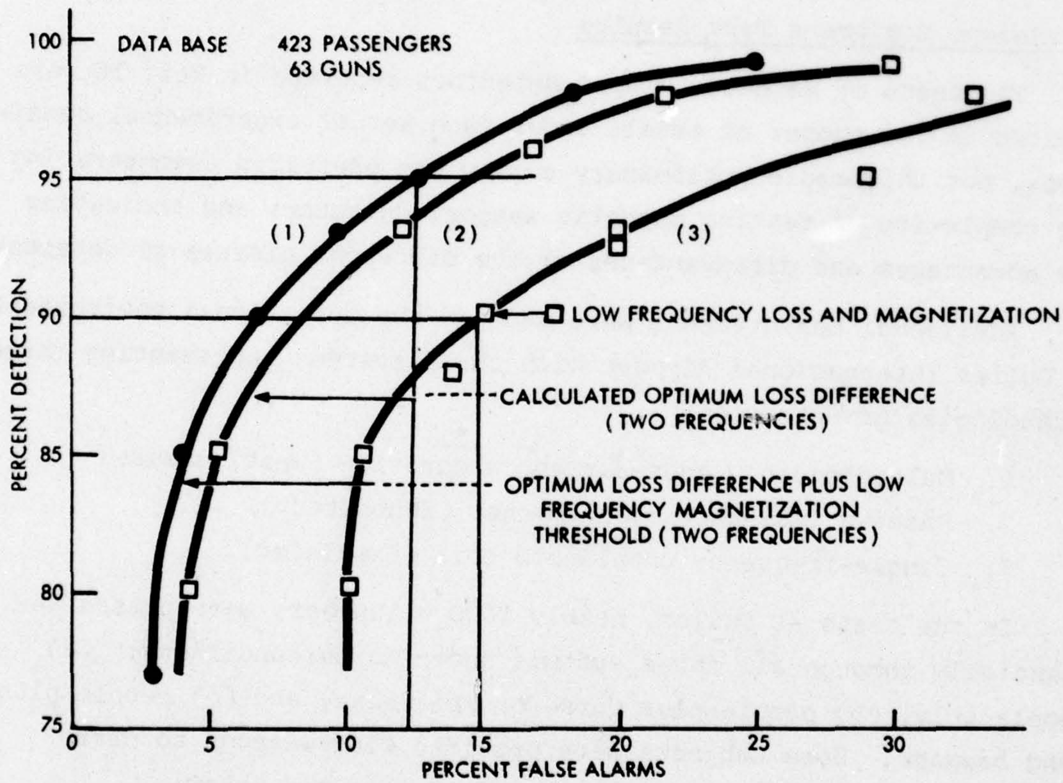


FIGURE 4. Magnetic Gun Detector Performance as a Function of Detection Method (Ref. 37)

From these preliminary tests, the feasibility of developing the capability for a 95 percent detection probability with only a slightly higher false-alarm rate than the present one seems assured. A remaining question is whether these present sensors can be further improved.

Experience has indicated that the more sophisticated the detector and the more parameters it considers, the better will be its capacity

to recognize weapon signatures and reject false alarms. (For example, the Westinghouse system uses two frequencies, three orthogonal magnetic fields, and extensive logic circuitry for the discrimination of weapons from other metallic objects.)

5. Some Magnetic Measurements Possibly Applicable to Weapons Detection

a. General. To illustrate the amount of information available from well-instrumented magnetic field measurements, we cite the simple case of a conducting, magnetic sphere. The field induced in a conducting, magnetic sphere by a uniform alternating magnetic field depends on the conductivity, permeability, and size of the sphere and on the frequency of the applied field. At very low frequencies eddy currents are negligible, and the perturbation of the applied field due to the sphere (i.e., the secondary field) is determined primarily by the permeability. At very high frequencies the effects of eddy currents are dominant, and the polarity of the perturbation field is reversed from its direction at low frequencies. There is an intermediate frequency at which the perturbation field is entirely at quadrature (i.e., 90 deg out of phase) with the applied field. Ward (Ref. 38) has shown how an appropriate set of measurements of the secondary fields at several frequencies can be used to determine the

- Conductivity
- Permeability
- Radius
- Position

of the sphere. Interestingly, these properties can all be determined with relative field measurements, so that absolute calibration is not required. Accurate measurements of both the applied and secondary fields are required, however.

Under the influence of a uniform applied field the sphere acts as a dipole oriented in the direction of the applied field. Though bombs or grenades may approximate spheres in shape, handguns and most metallic clutter do not. The perturbation fields from these

objects can be expected to contain terms due to higher order multipoles. These higher order terms decrease more rapidly than the dipole term as the distance from the object is increased. Thus, field measurements made at large distances from the object will be dominated by the dipole term, and Ward's analysis would be applicable. However, the total effect of the weapon may be small, so that observations of the perturbation field can be made only at short distances, and the effects of higher order multipoles may not be negligible. Under these circumstances, either some of the measurements suggested by Ward will not be possible or they will lead to artificial values for the electrical, magnetic, and physical characteristics of a sphere. Even so, these measurements may be useful in distinguishing weapons from metallic clutter if the shapes and electromagnetic properties of objects in the two groups are sufficiently different. A measurement program to test the applicability of Ward's analysis to weapon detection would be desirable.* In conjunction with such a program there should be analytical effort to investigate the extension of this approach to more complex objects.

b. Theory. For convenience, we summarize below the results obtained by Ward.

The center of the sphere is chosen as the origin of coordinates, the direction of the applied field is chosen as the vertical or z-direction, the magnitude of the applied field is H_o, and its angular frequency is ω. Then the z-component of the perturbation field is given by

$$H_z(\omega) = \frac{P}{4\pi}\left[-\frac{1}{r^3} + \frac{3z^2}{r^5}\right],$$

*In conducting such a program, the possible interference of low-frequency magnetic fields with heart pacemakers cannot be ignored. (Tests at higher frequencies are not necessarily applicable.)

where

$P = -\frac{3}{2} R^3 H_o(M + iN)\ 4\pi$,

R is the radius of the sphere,

$r = \sqrt{z^2 + s^2}$, where s is the distance of the observation point from the z-axis, and

M + iN is a specified function of the electromagnetic properties (permeability, conductivity, etc.) of the sphere and the surrounding medium.

This result assumes that the radius of the sphere is small compared to the wavelength of the applied field in the surrounding medium. P is the equivalent dipole moment of the sphere, M is the in-phase component, and N is the quadrature component. For applied fields that are small, hysteresis effects can be ignored, and the ratio of μ_1 (the permeability of the sphere) to μ_2 (the permeability of the surrounding region) can be assumed to be independent of field strength. The general behavior of M and N is shown in Fig. 5 (Ref. 38). The parameter θ is defined as $(\sigma_1 \mu_1 \omega)^{1/2} R$, where σ_1 is the conductivity of the sphere. M approaches asymptotic values at low and high values of ω, and $N \to 0$ at these limits. As $\omega \to 0$

$$P \to \left(\frac{\mu_1 - \mu_2}{\mu_1 + 2\mu_2}\right) H_o R^3 4\pi$$

and as $\omega \to \infty$

$$P \to -\frac{H_o R^3}{2} 4\pi .$$

If, at a fixed point, the value of H_z is measured at both a very low frequency and a very high frequency, then the ratio of these measurements yields

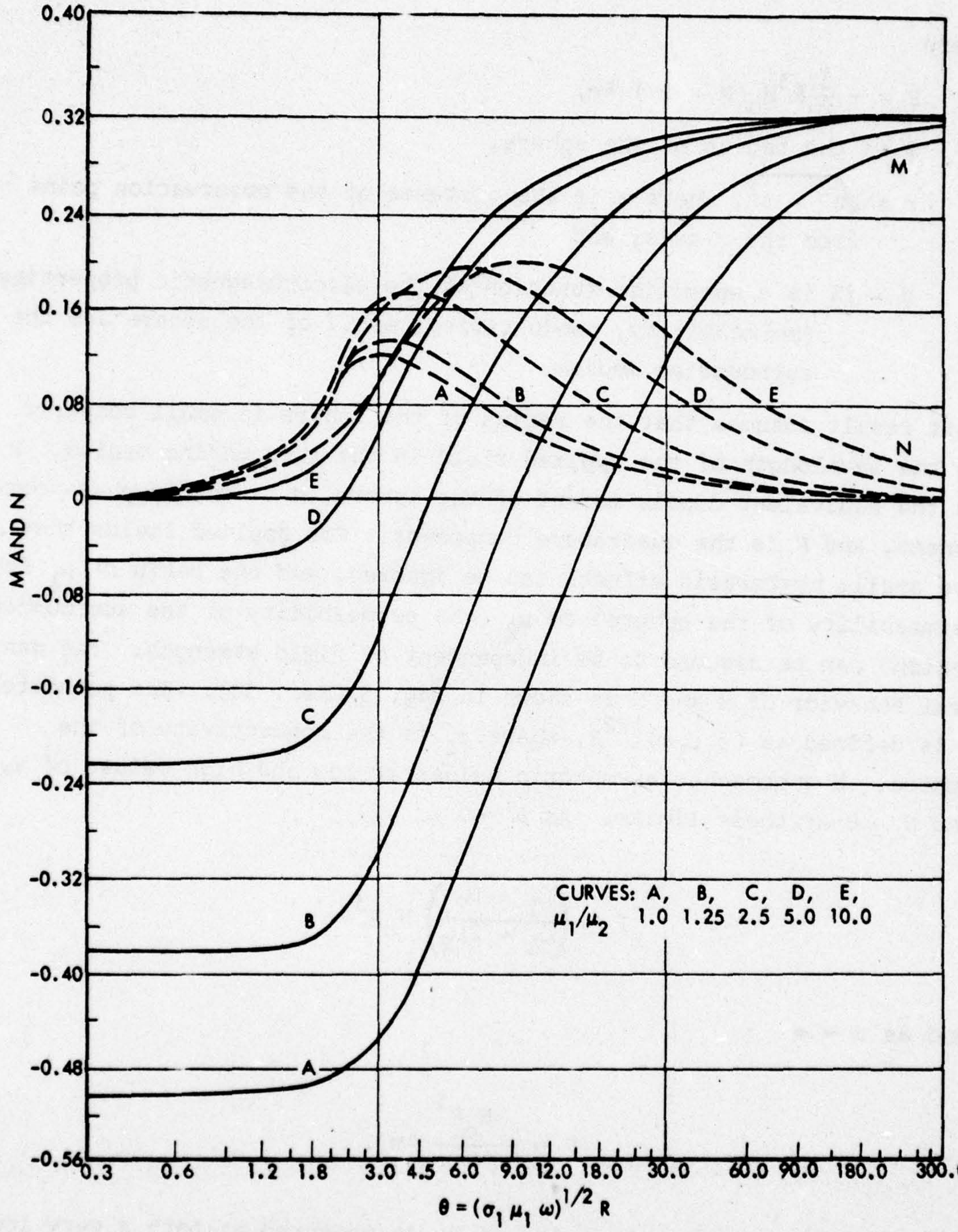


FIGURE 5. In-Phase and Out-of-Phase Components of Induced Dipole Moment of a Conducting, Permeable Sphere in a Uniform Field for Various Values of Permeability Contrast (Ref. 38)

$$\frac{H_z(0)}{H_z(\infty)} = -2\left(\frac{\mu_1/\mu_2 - 1}{\mu_1/\mu_2 + 2}\right),$$

and the ratio μ_1/μ_2 can be determined from these measurements. Since μ_2 is the permeability of air, the permeability of the sphere can be determined uniquely.

The location of the sphere is easily determined. Differentiation of H_z with respect to z shows that H_z has extreme values at $z = 0$ and $z = \pm (3/2)^{1/2}s$, where s is the horizontal distance from the measurement position to the z-axis. Measurement of H_z along any vertical line (with ω fixed) will locate the extreme values of H_z and so will determine z and s (and thus r) for all points along this vertical line. This is adequate for the further determination of the electromagnetic properties of interest. However, the direction of the origin from the vertical line can be determined by measuring the direction in which the horizontal component of the secondary field is a maximum. This locates the sphere unambiguously.

With the origin of coordinates now located, the radius of the sphere can be determined from either the low-frequency value or the high-frequency value of $H_z(\omega)$. Inserting the high-frequency value of P into the expression for $H_z(\omega)$ leads to

$$R^3 = \left(\frac{2H_z(\infty)}{H_o}\right)\left(\frac{(z^2 + s^2)^{3/2}}{[1 - 3z^2/(z^2 + s^2)]}\right).$$

The ratio $H_z(\infty)/H_o$ can be measured at any point, and the value of z and s for that point can also be determined, so that R is uniquely determined. Use of $H_z(0)$ leads to a similar result but requires use of the ratio μ_1/μ_2.

Referring to Fig. 5, we see that for each value of μ_1/μ_2 there is a distinct value of θ for which M, the in-phase component of the perturbation field, takes the value of zero. Ward finds that this

value of θ, denoted by θ_c, is linearly related to the ratio μ_1/μ_2; i.e., $\theta_c = 1.84\ \mu_1/\mu_2$. If the in-phase component of the perturbation field is measured at any position, and if ω is varied until this component vanishes, then σ_1 can be calculated from the equation

$$1.84\ \mu_1/\mu_2 = (\sigma_1 \mu_1 \omega)^{1/2} R$$

since σ_1 is the only unknown quantity. This provides a measurement of the conductivity of the sphere.

c. Comment. This analysis of Ward permits the determination of the permeability, conductivity, size, and position of a sphere by varying the frequency of a uniform applied magnetic field. The application of this analysis to the detection of concealed weapons is open to question. It must be determined whether weapons and metallic clutter individually induce secondary fields sufficiently close to dipolar for the analysis to apply, whether the properties of weapons and clutter are sufficiently distinct to be distinguishable with reasonable probability, and whether this distinction is possible when both clutter and weapons are present.

If the analysis is useful and can be extended to antihijacking operations, then the questions of system cost and utility arise. A system suitable for analysis of this kind is more complex and requires more highly controlled fields than current magnetometers. Adaptation of such a system to automatic detection would be difficult and expensive. Examination of these problems is premature until the feasibility of the approach has been demonstrated.

6. Recommendations

Areas of R&D that may provide major performance improvements in the magnetic detection of concealed weapons are:

- Studies of coil designs to improve the uniformity of the imposed AC fields.

- More sophisticated measurements to determine whether Ward's analysis can be used to recognize signatures of weapons from metallic clutter. These measurements should include:

  (a) The determination of the ratio of field strengths at high and low frequencies. This can yield permeability.

  (b) The effects of location and size.

  (c) The determination of the frequency at which the in-phase component of the induced field vanishes. This can yield the conductivity.

- Additional theoretical analysis of the magnetic perturbation by other metallic shapes (i.e., a cylinder) and multiple sources, such as a pair of spheres.

- Investigation of multifrequency systems to determine the enhancement of signature information, including perhaps the addition of a third frequency to the Westinghouse system or the development of a swept-frequency system.

With such information it would be possible to assess the likelihood of making substantial advances in gun detection beyond the present state of the art.

III. IMAGING TECHNIQUES

A. TELEVISION IN THE VISIBLE FREQUENCIES

Although conventional television in the visible spectrum might, in a few circumstances, permit the observation of concealed weapons and perhaps even explosives by virtue of a camera vantage point above or below a suspect, the technique is of such limited applicability as to be unworthy of further consideration.

The use of television for general surveillance of unattended baggage areas and aircraft is of course a standard commercial security measure.

B. MAGNETIC MAPPING AND DISPLAY

The objective of this technique is to sense, process, and suitably display changes in the ambient magnetic field caused by the presence of metallic objects. The form of the display (on a cathode ray tube, for example) would be such as to permit recognition of an object producing distortion of the magnetic field.

A possible system of this kind, proposed by the Bio-Medical Engineering Technological Institute of Northwestern University, relates to the development of a new type of television camera tube that is sensitive to magnetic fields. The magnetosensitive element in the conversion layer would be a semiconductor device working on the principle of controlled lifetime of injected carriers by an external magnetic field. The material proposed for use features very high magnetosensitivity relative to other known magnetosensitive materials.

The first phase in development would be a determination of the feasibility of constructing such an area display device. Thereafter,

each phase of the program would, of course, be contingent on the successful completion of the previous phase. Studies would be necessary for fabrication of the device in a form that lends itself to miniaturization in a multi-element display device. A final phase would be the construction of a limited number of television camera tubes for evaluation.

The Northwestern proposal (Ref. 39) suggested the use of a conducting faceplate target tube developed under an Atomic Energy Commission contract. This tube is shown in Fig. 6. The proposal contends that "the tube lends itself to experimental studies of the feasibility and sensitivity of the proposed system in that small discrete magnetosensitive elements may be found in an array which subsequently is connected to the plug target tube for display, using television scanning techniques." The proposal continues, "It is proposed to form such an array using magnetodiodes, available commercially from the Sony Corporation. Initially, it is planned to use a fifty element array, which will result in image detail in the order of approximately five lines per inch. Using this experimental array, the sensitivity, the speed of response, and general spatial orientation of the system may be investigated. Assuming this portion of the project is successful, then an extended-area array, using elements in the order of the one square millimeter, could be fabricated."

This program may prove feasible, but it is difficult to see how such a sensor can be made to display, in a fashion usable for antihijacking application, a recognizable image of an object causing magnetic field distortion. Competitive techniques, described in the following sections, would seem to have a number of advantages.

C. ULTRASONIC IMAGING

The use of ultrasonic beams to detect scattering objects has provided the basis for sonar development. At ultrasonic frequencies (20-100 kHz), the wavelengths in air range from 16.5 to 3.3 mm. These wavelengths offered the prospect that objects of gun size could be

imaged with encugh detail to be recognizable (Ref. 1). However, the reflection of cloth and body and the absorption of cloth were expected to be so high that the detection of concealed weapons on the person was not considered likely. However, the reflection and absorption characteristics of clothing and body could only be estimated, since measurements at ultrasonic frequencies were not available.

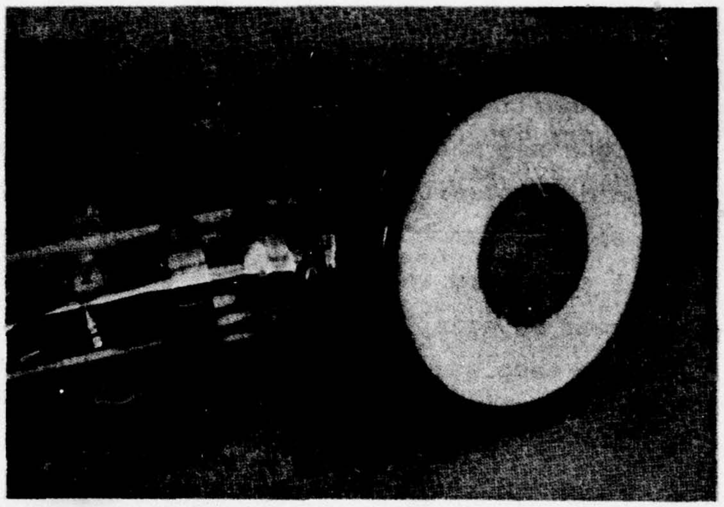
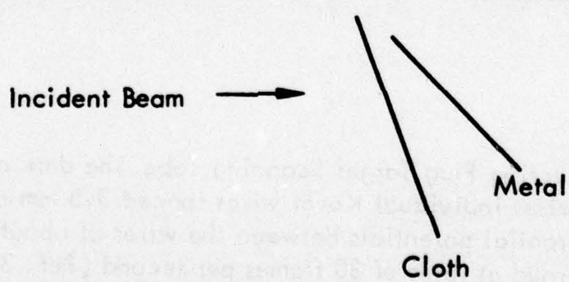


FIGURE 6. Conducting Plug Target Scanning Tube. The dark area of the faceplate comprises individual Kovai wires spaced 0.5 mm center to center. Differential potentials between the wires of about 5×10^{-2} volts may be discerned at rates of 30 frames per second (Ref. 39)

The U.S. Army laboratory at the Mobility Equipment Research and Development Center (MERDC) recently undertook a measurement program to determine whether detection of concealed weapons by ultrasonic means is feasible. Frequencies from 20 to 100 kHz were used, and four samples of cloth were tested. Findings can be summarized as follows:

- Transmission of the four cloth samples varied from 15 to 65 percent throughout the frequency range. It was greater than 20 percent at 100 kHz for all samples.
- Reflection of the cloth samples at 100 kHz varied from 5 to 50 percent.
- Reflection from small parts of the body, such as the thumb or palm, varied from 95 to 98 percent throughout the frequency range.
- Reflection from a flat metal plate behind a cloth screen was measured at 100 kHz in the geometry shown below. The platform holding the cloth and metal was rotated so that all scattering angles could be observed. In all cases, the largest reflection peak was from the cloth. With some samples of cloth, a small secondary reflection from the metal plate could be observed superimposed on the diffuse cloth reflection. For other samples, there was no detectable return from the metal plate.



These measurements confirm expectations. Even the diffuse reflections from cloth dominate the returns from a concealed metal plate. In addition, the high body backscatter that was measured would obscure the return from a gun concealed on the body.

The work at MERDC shows that, for the cloth samples examined, the two-way transmission varies from 2 to 42 percent. This sets an

upper bound on the energy available from weapon scattering. In the absence of other reflections, signal returns with these strengths would be detectable. If the body and clothing reflections could be suppressed, the transmission of a wider range of clothing materials would then be of interest.

Future work on ultrasonic imaging is not justified unless techniques can be devised to suppress the reflections from clothing and body without adversely affecting the weapon return. At present, there are no promising processing techniques that would warrant continued effort in the application of ultrasonic imaging to the detection of concealed weapons.

D. X-RAY IMAGING

1. Introduction

The technical feasibility of X-ray imaging for the detection of concealed handguns was considered in Ref. 1. With present technology, it is possible to obtain a high-definition X-ray image which will subject the body of a person to a dose of less than 0.1 mrad. The probability of detecting a concealed metallic handgun with such imagery should be near unity with an attendant false-alarm probability near zero, a performance which cannot be matched by any other known sensor at the present time. In Section III-D-2 below, an expanded and updated discussion of X-ray imaging technology for anti-hijacking application is presented, with emphasis on personnel inspection. This is followed by a discussion of the benefits and risks involved in X-raying a significant fraction of the flying population. A discussion of the natural and man-made radiation environment and of radiation-induced cancer is presented in Appendix B.

2. X-Ray Technology

There presently exists a prototype X-ray system which could be incorporated into an anti-hijacking system* for the detection of

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*Profile screening, metal detection, and search could constitute the other components of an anti-hijacking system (Appendix C).

concealed handguns. Details of this Bendix system are discussed in Ref. 40. Briefly, the principle of operation is as follows. A short-pulse beam of X-radiation is emitted from a source, casting an X-ray shadow of the subject on a detector screen, which converts the X-ray quanta into a visible image. An objective lens focuses this dim image on the photosensitive surface of an image intensifier. The output of the intensifier is imaged on the surface of a television pickup tube with transfer optics, using either lenses or fiber-optic elements. The video signal from the TV camera is stored in either a modified single-pulse tape recorder or a solid-state storage unit and is immediately played back over a television monitor for operator inspection.

The Bendix system concept has three significant disadvantages compared to an alternative scanning technique. Foremost among these is the poor light photon collection efficiency of even the best available objective lens such as the f/1.5, 18-mm focal length lens custom made by Angenieux Corporation of France. To cover an 8-ft format, it was necessary to place this lens a distance of 3.8 ft from the detector screen. Thus, the fraction of the light photons collected with this 10-inch aperture retrofocus lens, if one assumes a screen with a perfectly reflecting mirror backing, is less* than

$$\frac{\frac{\pi}{4}\left(\frac{1.8}{2.54\text{x}12}\right)^2}{2\pi(3.8)^2} = 3 \times 10^{-5}$$

The ZnCdS screen used has an energy absorption conversion efficiency of approximately 15 percent. A light photon at approximately 4400 Å wavelength has an energy of approximately 3 ev. Thus, for each 150-kev

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*3.8 ft is the minimum distance between the screen and lens, the top and bottom of the screen being 5.5 ft from the center of the lens. There are also transmission losses in this complex multi-element lens and in the transfer optics.

X-ray photon incident on the screen, one may expect 7,500 visible light photons to be generated, but only $7500 \times 3 \times 10^{-5} = 0.225$ photon to be imaged by the lens. Finally, for detection, each light photon must be converted to a photoelectron by a photocathode. The RCA 4463 photomultiplier tube used has an S-20 spectral response* which has a typical quantum efficiency of 18 percent** at its wavelength of maximum response at 4200 Å. The expected number of photoelectrons generated for each incident X-ray photon is therefore $0.225 \times 0.18 = 0.04$, which means that 25 X-ray photons must be incident on the screen before one can expect to detect a single photoelectron. The expected minimum dose required for imaging with the Bendix system would therefore be 25 times greater than that obtainable with the scanning X-ray system proposed by American Science and Engineering, discussed below. Since the measured minimum dose of the Bendix system is 2-3 mrad, the expected minimum dose of the American Science and Engineering system would be no more than ~ 0.1 mrad.

A second significant disadvantage of the Bendix system is that radiation is scattered by the object under examination and hence degrades the quality of the image. This scattered flux is approximately equal to the primary radiation for a chest X ray, but may be 10 or more times greater for the abdomen (Ref. 41.) Thus, in the latter case, if two regions of an object under examination differed in contrast by 10 percent in the absence of scatter, the contrast would be reduced to only 1 percent, which is insufficient to be detected by the human eye viewing a TV image. In a scanning system such as that proposed by American Science and Engineering (Fig. 7) the only radiation that will be picked up by a moving NaI crystal detector is from the radiation that passes through a narrow lead-formed entrance slit placed along the length of the detector. The width of this slit may be made equal to the flying-spot pencil beam, or 2 mm, which in general is not more than 1/500 of the width of the

*RCA Photomultiplier Manual.

**RCA Electro-Optics Handbook.

image itself. It, therefore, follows that only 1/500 of the total scattered radiation would be detected at any instant of time as background radiation. For all practical purposes, scattered radiation is eliminated in a scanning system and the contrast obtained in the image is greatly improved, particularly over the thick regions of the body where a handgun is quite likely concealed.

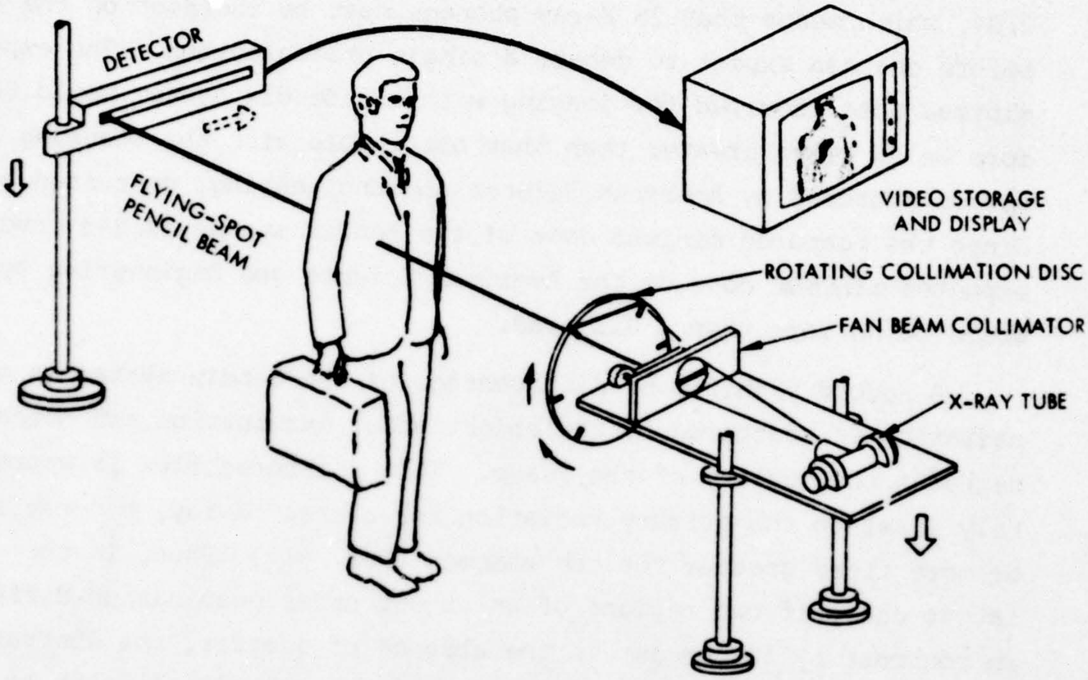

FIGURE 7. Principle of Operation of Flying-Spot Imaging System (FSIS) (Ref. 41)

Finally, the Bendix system has the disadvantage of a very large and hence costly detection screen, 3 x 8 ft, a complex and costly objective lens ($8,000 for the Angenieux), and a costly image intensifier plus transfer optics. In the flying-spot scanning system, a strip detector 0.5 inch wide and 3 ft long will suffice, and neither an objective lens nor an image intensifier is required. However,

mechanical scanning equipment is required. In Figs. 7 and 8 (Ref. 41) the scheme proposed involves moving the X-ray machine with its rotating and slit collimators in parallel with the detector. In an alternative scheme the subject could be moved on an elevator and the X-ray machine and detector allowed to remain stationary.

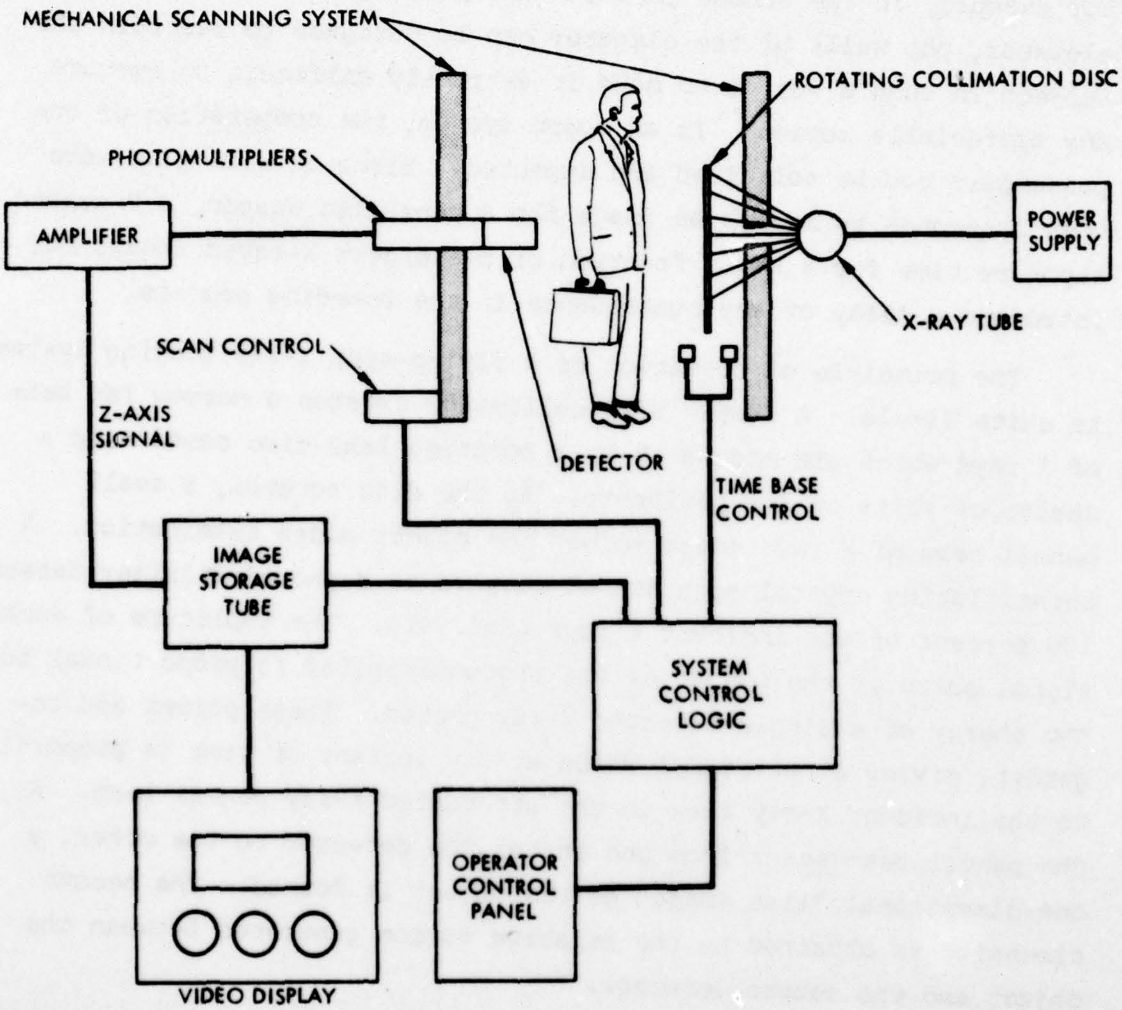

FIGURE 8. Block Diagram of FSIS (Ref. 41)

There seems to be only one significant performance disadvantage to the flying-spot scanning system. As proposed by American Science and Engineering, it requires 2 seconds for an exposure which imposes motion limitations on the subject. Slight motions can be tolerated, inasmuch as they will only introduce distortion in the imagery and not degrade resolution. Gross motions, however, cannot be tolerated and introduce a procedural problem, but one which is not insurmountable. For example, in the scheme in which the passenger is confined in an elevator, the walls of the elevator can be designed to restrain the subject in such a way as to make it extremely difficult to execute any appreciable motion. In an overt system, the cooperation of the passengers can be solicited and expected. Since it will take more than 2 seconds to search an image for a concealed weapon, a 2-second exposure time for a small fraction of passengers X-rayed should not introduce a delay of any consequence in the boarding process.

The principle of operation of a flying-spot X-ray imaging system is quite simple. A simple slit collimator creates a narrow fan beam of X rays which are modulated by a rotating lead disc containing a series of slits on its periphery. As the disc rotates, a small pencil beam of X rays moves across the object under examination. A scintillating crystal such as NaI coupled to a photomultiplier detects 100 percent of the indicent X rays (Ref. 41). The amplitude of each signal pulse at the output of the photomultiplier is proportional to the energy of a single detected X-ray photon. These pulses add together, giving a net signal which at any instant of time is proportinal to the incident X-ray flux in the attenuated X-ray pencil beam. As the pencil beam scans from one end of the detector to the other, a one-dimensional "live image" of the object is formed. The second dimension is obtained by the relative motion generated between the object and the source-detector.

In a proposed 2-mm resolution system (Ref. 41) it is calculated that a dose per image of only 0.03 mr will yield 25 photons/resolution element, assuming a body thickness of 30 cm and using 125-kvp X rays. The dose could be reduced by relaxing the image resolution requirement.

The concept of a scanning X-ray system was first published by Moon in 1948 (Ref. 42). Subsequently built mechanical scanning systems (Refs. 43-45) have been applied to fluoroscopy and fluorography of gamma radiation from patients treated with radioactive isotopes (Ref. 46). It is indeed distressing to find that X-ray scanning technology has been allowed to lapse for 15 years in view of the large doses of radiation to which the population is being subjected in medical diagnostic roentgenology.

A scanning X-ray system is particularly well suited to the task of baggage inspection. One of the dimensions of the image can be fortuitously generated by the motion of the conveyor belt (Fig. 9). The principle of operation is identical to the personnel scanning system described above. Laboratory system results for a system with resolution better than 1 mm x 1 mm delivered a measured dose of less than 0.001 mrad to parcels (Ref. 41). In the present Baird-Atomic X-ray baggage inspection system, a 0.15-sec exposure time makes it necessary to stop the conveyor belt traveling at 75 ft/min to avoid a smeared image, and a dose of 1-5 mrad* is delivered to the object. Since such a dose is unlikely to be harmful--even to luggage containing photographic film, biological specimens, and pharmaceuticals--perhaps the chief performance advantage of the scanning system for baggage inspection is its scatter-free image. Equipment cost may be the determining factor in deciding whether or not the scanning system is to be the preferred system. The smaller object size results in a smaller detector and simpler optics, which reduces the hardware advantages for the scanning system cited above for inspecting personnel. Bendix has also developed a portable X-ray system weighing approximately 150 lbs. The 110-kv source radiates a 60-nanosecond pulse and weighs only 12 lb. A 3-stage image intensifier and vidicon provide

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*Only two stages of intensification were used, providing a gain of 2,000.

a resolution of approximately 5 line pairs/inch. The dose is 0.05 mrad at a distance of 4 ft.

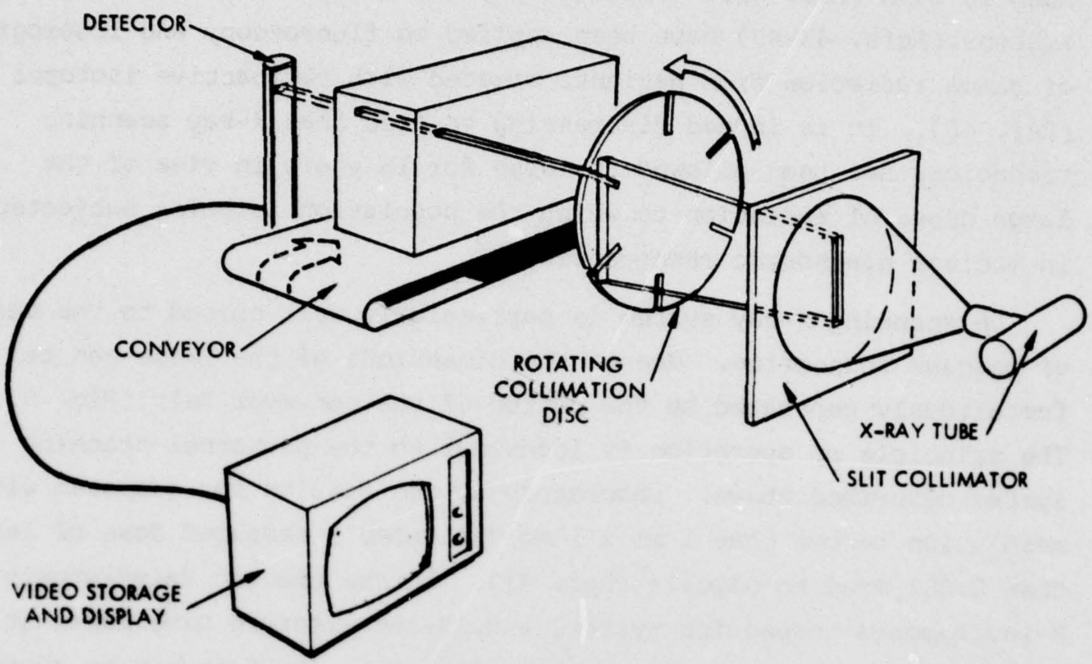

FIGURE 9. Principle of Operation of Laboratory FSIS (Ref. 41)

One of the principal operational disadvantages of an X-ray imaging system is the necessity for a human operator to view and inspect a succession of X-ray images. The costs of operating X-ray imaging machines on a 24-hour/day basis will quickly overwhelm the initial investment costs. In addition, operator fatigue could be expected to reduce the probability of detection from the very high value inherent in the system. This difficulty could be overcome if the detection process were automated. This may be accomplished by giving up shape information in the image and employing contrast alone to detect a gun or bullet. Development and testing of a contrast detection system is recommended to determine whether the increased false-alarm probability of such a system is tolerable.

3. Benefits Versus Risks

For an anti-hijacking application of X rays, both the benefits and the risks are extremely difficult to predict quantitatively. The benefits are obviously a function of the incidence of aircraft hijacking attempts, but this incidence two or more years in the future is unpredictable. Likewise unpredictable is the incidence of hijacking attempts resulting in a loss of aircraft (one historical event to date in Jordan, 1970) or, most important of all, the expected number of hijack-induced passenger fatalities per year (no historical large-scale event to date). The somatic risks of very low dose radiation to the population are poorly understood at the present time, but it is known that the incidence of most, if not all, cancers is increased with exposure to relatively large doses of radiation. It is also known that harmful genetic mutations in the future population can be expected from exposure to ionizing radiation. The magnitude of this genetic risk is uncertain for the human population as a function of dose, but it is generally agreed (Ref. 47) that there is a linear relationship between mutation rate and dose rate. In the case of radiation-induced carcinogenesis, there is no agreement on a linear dose-response relationship. There is a possibility that a low dose threshold exists, below which harmful somatic effects do not occur. Indeed, there is even some evidence that indicates the surprising possibility that low dosage levels at low dose rates can have the effect of lengthening life. This is quite commonly observed with laboratory animals, and is sometimes called the "102 percent effect" because the life span is increased about 2 percent (Ref. 48). However, prudence dictates a conservative approach to the problem of low dose radiation effects, and hence in the mathematical model constructed below to estimate the carcinogenic risk to the flying population, the linear dose-response relationship will be assumed to hold.

This purpose of the mathematical model is to calculate an upper bound on the magnitude of the carcinogenic risk, which may be of more direct concern to the flight passenger than some remote and exceedingly small risk to his unborn descendants.

While any calculation of absolute risk from low dosage radiation is of dubious validity, calculation of the relative risks involved between two different levels of radiation exposure is on much firmer ground, if one assumes the validity of a linear dose-response relationship over the limited dose ranges of interest. Thus, a dose of kx mrad would be expected to result in a response or risk that would be k times larger than a dose of x mrad. It is for this reason that the expected anti-hijacking X-ray dose should first be compared with the risks already being taken from the natural environmental background and from man-made sources of radiation. The most pertinent comparison in the present application is the dose of natural space radiation received by a flight passenger at a typical jet aircraft altitude of 35,000 ft.

4. Flight Radiation Dose

The atmosphere of the earth acts as a screen for the cosmic rays originating in the sum and galaxies. The attenuation effect is a function of altitude and geomagnetic latitude. From Fig. 10* it is seen that at a geomagnetic latitude of 45 deg and an altitude of 35,000 ft, a passenger will absorb a radiation dose of 0.2 mrad/hr. Aircraft provide at most only 1-g/cm^2 shielding around crew and passengers, which will not greatly alter the calculated dose rates. A transcontinental jet flight between New York and San Francisco of approximately 5 hours will subject each passenger and crew member to approximately 1 mrad or an order of magnitude higher dose than that received by a passenger from a 0.1-mrad anti-hijacking X ray. A shorter 1.5-hour flight, corresponding more nearly to the duration of an average jet flight** will still subject each passenger and crew to a dose of 0.3 mrad, which is three times the risk from a 0.1-mrad anti-hijacking X ray.

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* Based on tabulated data in Ref. 49.

** Average length of haul for domestic trunk lines in 1969 was 769 miles (Ref. 50).

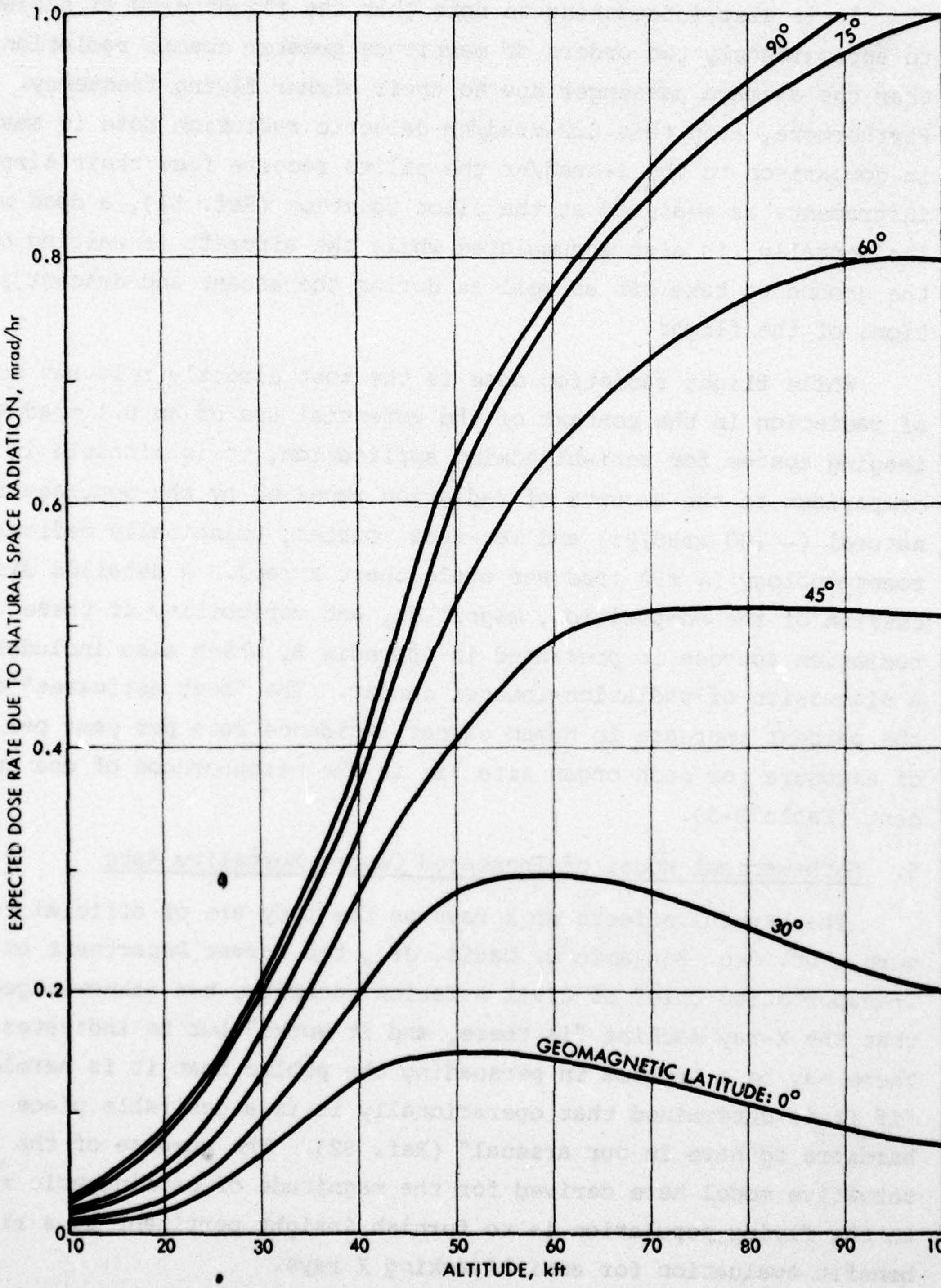

FIGURE 10. Expected Dose Rate Due to Natural Space Radiation as Function of Altitude and Geomagnetic Latitude (Ref. 49)

It is also interesting to note that the flight crew is subjected to approximately two orders of magnitude greater cosmic radiation than the average passenger due to their higher flying frequency. Furthermore, even this 0.2-mrad/hr galactic radiation dose is small in comparison to the 1-mrad/hr the pilots receive from their airplane instruments as measured at the pilot position (Ref. 51), a dose which, incidentally, is also accumulated while the aircraft is waiting on the ground to take off as well as during the ascent and descent portions of the flight.

While flight radiation dose is the most directly relevant source of radiation in the context of the potential use of an 0.1 mrad X-ray imaging system for anti-hijacking application, it is minuscle in comparison to the amounts of radiation received by the populace from natural ($\sim$ 100 mrad/yr) and man-made sources, principally medical roentgenology ($\sim$ 150 mrad per whole chest X ray). A detailed discussion of the composition, magnitude, and variability of these radiation sources is presented in Appendix B, which also includes a discussion of radiation-induced cancer. The "best estimates" of the percent increase in human cancer incidence rate per year per rad of exposure for each organ site lie in the neighborhood of one percent (Table B-3).

5. Mathematical Model of Increased Cancer Mortality Rate

The harmful effects of X rays on the body are of official concern. Lt. Gen. Benjamin O. Davis, Jr., the former Department of Transportation Chief of Civil Aviation Security, has acknowledged that the X-ray machine "is there, and it works" but he indicates there may be a problem in persuading the public that it is harmless "if it is determined that operationally it is a desirable piece of hardware to have in our arsenal" (Ref. 52). The purpose of the conservative model here derived for the magnitude of carcinogenic risk to the flying population is to furnish insight pertinent to a risk-benefit evaluation for anti-hijacking X rays.

The age-specific mortalities for males in the United States due to all malignant neoplasms in 1966 is given in Fig. 11 (Ref. 53). Domestic hijackers have been almost exclusively male adults and it is, therefore, possible that females would be exempted from anti-hijacking X rays. Female exemption would be desirable, since a fetus is especially sensitive to radiation during the early months of pregnancy.* The higher susceptibility of children to harmful radiation effects would also make their exemption from anti-hijacking X rays desirable. In this model it is assumed that only male adults 20 years of age or over are candidates for anti-hijacking X rays. For purposes of calculation, an upper age limit of 70 years of age seems reasonable.

A uniform distribution of 2 percent passenger population per one-year age group in the 20-70 year old male population is assumed. This assumption is approximately correct, as is evident from Table 15 (Ref. 54).

TABLE 15. PASSENGER POPULATION DISTRIBUTION BY AGE GROUPS (Ref. 54)

Passenger Age	% of Passengers	% of Passengers per One-Year Age Group
18-24	20	2.8
25-34	19.9	2.0
35-49	31.5	2.1
50 +	28.6	---

The age-specific male mortality per person per year in the United States due to all malignant neoplasms can be approximated by the expression

$$I(A) = 10^{-6}\, e^{[(A+30)/10.85]} \qquad 20<A<70 \qquad (1)$$

for men between 20 and 70 years of age A as can be seen from Fig. 11.

*But the radiation dosage from flying would be greater than from X-ray screening.

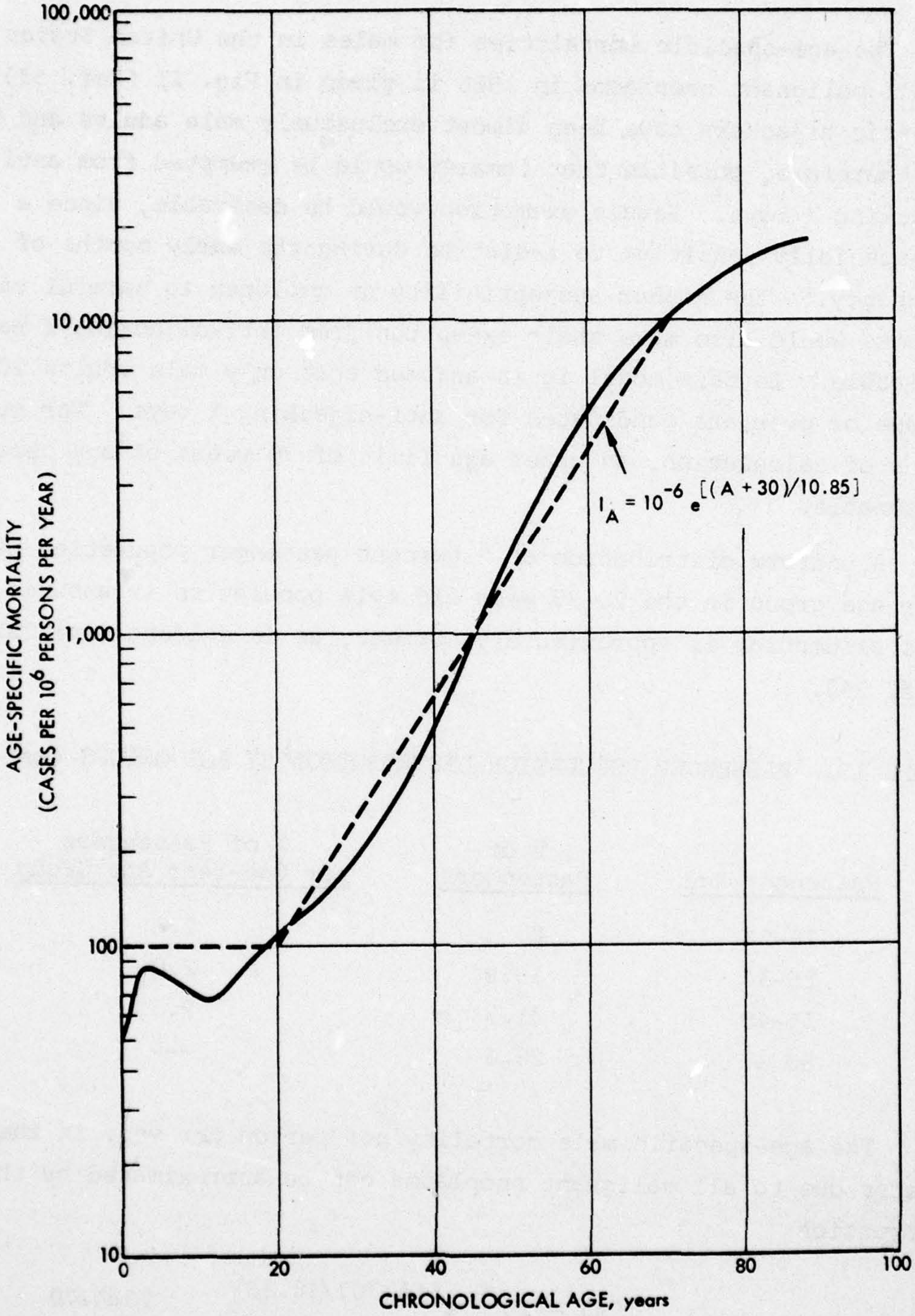

FIGURE 11. Age-Specific Mortalities, Male, All Malignant Neoplasms (Source of solid curve: Ref. 53)

A steady-state situation will be assumed in which a passenger of age A will have accumulated an anti-hijacking X-ray dose proportional to his age. Thus, the expected increase in the annual number of cancer deaths in the United States due to anti-hijacking X rays can be approximated by

$$E = \int_{20}^{70} (0.02)Nf\, D(A-20)\, \alpha I(A) dA \tag{2}$$

where

N = total number of male adult* revenue passengers carried per year in USA.

f = expected fraction of adult male passengers X-rayed.

D = X-ray dose in rads per exposure.

α = fractional increase in cancer incidence rate per year per rad of exposure.

$I(A)$ = age-specific cancer mortality rate.

It would take 50 years of system operation to build up to the steady-state value of E represented by Eq. 2.

Substituting Eq. 1 and evaluating the integral of Eq. 2,

$$E = 0.0874\ NfD\alpha \tag{3}$$

The expression for E after 20 years of system operation is

$$E = 0.02\ NfD\alpha \left[\int_{20}^{40} (A-20)\, I(A) dA + 20 \int_{40}^{70} I(A) dA \right] \tag{4}$$

*In 1969, 52.5 percent of airline passengers were male (Ref. 50).

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which reduces to

$$E = 0.0246\ NfD\alpha \tag{5}$$

Therefore, the 20-year value of E is 28 percent of the steady-state 50-year value which has been conservatively assumed in Eqs. 2 and 3.

In 1969, there were 1.59×10^8 revenue passengers carried by the U.S. scheduled airline industry (Ref. 50). Allowing for future growth, the number of male adult revenue passengers carried per year is assumed to saturate at a value $N = 2 \times 10^8$. Assuming $\alpha = 0.01$, Eq. 3 then reduces to

$$E = 1.75 \times 10^5\ fD \tag{6}$$

In Fig. 12, Eq. 6, the steady-state solution, is plotted. It is evident from this conservative linear dose-response model that the expected increase in the number of annual cancer deaths per year can be made negligibly small only if the X-ray dose per exposure and the expected fraction of passengers X-rayed are minimized. For example, if a magnetometer or some other procedure is used to screen X-ray candidates so that f = 0.1, then an X-ray dose per exposure of 0.06 mrad would result in only one* additional cancer death per year in a male population of over 100 million. It is interesting to note that since the entire flying population is subjected to an average dose of 0.3 mrad of galactic radiation per flight, f = 1, and more than 100 persons (including women and children) would be added to the annual cancer mortality list. This constitutes a risk comparable to that of aircraft crash fatalities. It is perhaps insensitive, but it is nevertheless important to point out that the bulk of these mortalities would be in the older age group, which has little lifetime remaining in any case.

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*To date, the life of only one passenger has been lost as a result of aircraft hijacking in the United States.

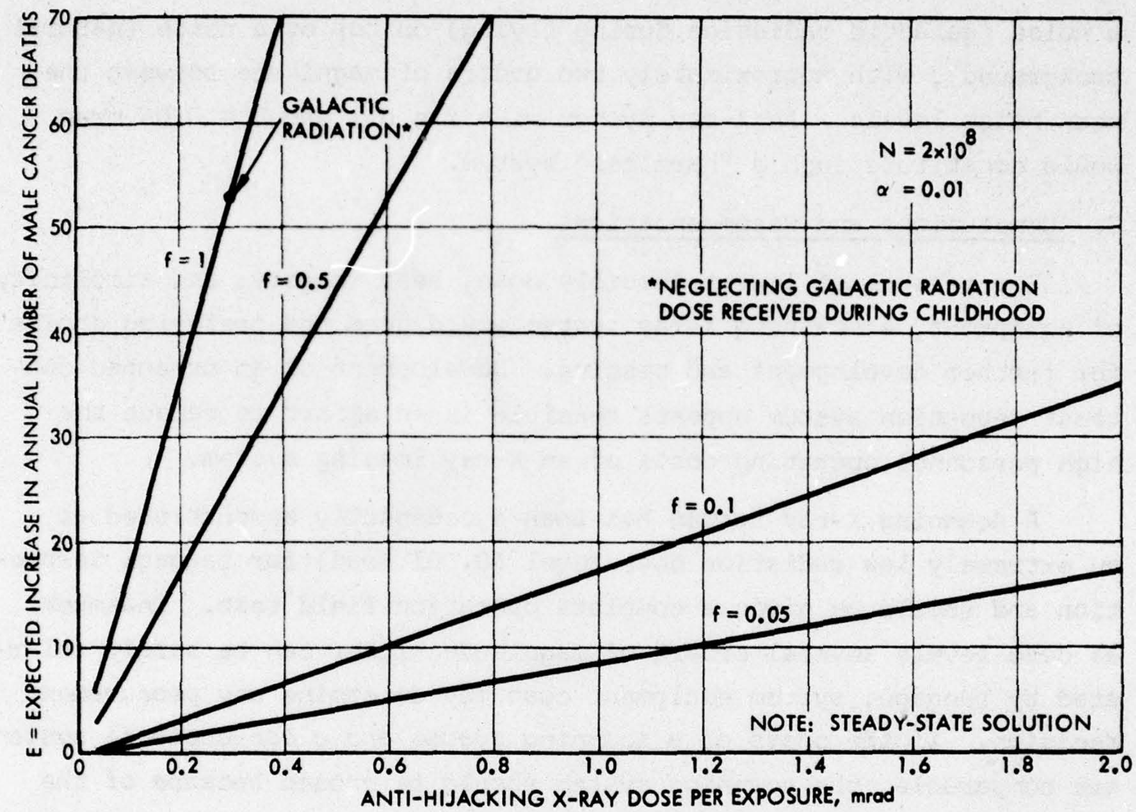

FIGURE 12. Expected Increase in Annual Number of Male Cancer Deaths Versus Anti-Hijacking X-Ray Dose per Exposure

With the absence of a probable and substantial high risk to human life from aircraft hijacking, it is recommended that a guideline for an anti-hijacking X-ray system be expressed in terms of the fraction of the risk from galactic radiation already accepted, albeit unconsciously, by the flying population. This would have the advantage of circumventing the many deficiencies inherent in any simplified model necessary for a calculation of the absolute number of increased cancer deaths and would also cover the genetic mutation risk. It is suggested that a level of risk for an anti-hijacking X-ray system which results in 1 percent of the risk from galactic

radiation absorbed during flying be defined and adopted as a "harmless" system. This anti-hijacking risk would constitute a noise on top of a noise (galactic radiation during flying) on top of a noise (natural background), with approximately two orders of magnitude between the mean noise levels. An X-ray system with f = 0.1 and D = 0.06 mrad would constitute such a "harmless" system.

6. Conclusions and Recommendations

For reasons of lowest possible dose, best imagery, and simplicity of equipment, a scanning X-ray system would seem the preferred choice for further development and testing. Development of an unmanned contrast detection system appears feasible in an effort to reduce the high personnel operating costs of an X-ray imaging system.

A scanning X-ray system has been successfully demonstrated at an extremely low radiation dose level (0.001 mrad) for baggage inspection and should be given a complete operation field test. Inasmuch as dose levels several orders of magnitude higher can be safely tolerated by baggage, system equipment cost may determine any procurement decision. If the costs of a scanning system and a conventional system are comparable, the scanning system should be chosen because of the scatter-free imagery that it provides.

It is recommended that a requirement be agreed upon by the cognizant governmental agencies with respect to the permissible radiation dose for an X-ray anti-hijacking system. A dose of 0.1 mrad per exposure does not appear to be unreasonable from either a technological or biological-risk standpoint, particularly if only some small fraction ($\leq$10 percent) of the flying population is likely to encounter such a system.

While there is little doubt that an X-ray imaging system would provide the most accurate and reliable means for "hands-off" searching of individuals, its efficiency in preventing hijacking would be limited to those instances wherein the weapon employed is opaque to X rays. To reduce the fraction of the population exposed to X-radiation, it

would seem prudent to use X-ray imaging in conjunction with another screening sensor. The potential costs and complexities of developing and employing such a system should be compared with those that would be involved in hand-searching selectees.

E. RADAR IMAGING

Many problems arise in the radar imaging of concealed weapons. Consideration must be given to the resolution and dynamic range achievable, the attenuation by clothing, the scattering characteristics of weapons and body, the effects of target motion, the power levels required, and the implementation of imaging detection systems. Until recently, the basic difficulty of obtaining adequate resolution and dynamic range has precluded successful imaging of weapons even under ideal circumstances. Recognizable images have now been obtained under highly controlled conditions (Fig. 13, from Ref. 55), so that even though much more knowledge of the process of image formation is required, some attention can also be given to the operational problems of detection of concealed weapons.

Fundamental problems of image formation arise at microwave and millimeter-wave frequencies due to the use of coherent illumination as well as to the wavelengths involved. The use of a single stationary source to illuminate a stationary target produces a scattering pattern which is unvarying in time. Thus, the return from each portion of the object remains constant throughout the period of observation. As a result, the specular returns from some parts of the object can greatly exceed the diffuse returns from other portions. This has two adverse effects. First, the strength of the specular returns can saturate the detection system, causing blooming as well as suppression of smaller returns. Second, even if the system dynamic range is adequate to process the returns without distortion, the wide dynamic range inherent in the returns results in strong variations in intensity across the image. This granular effect is commonly observed at optical wavelengths when laser sources are used for illumination.

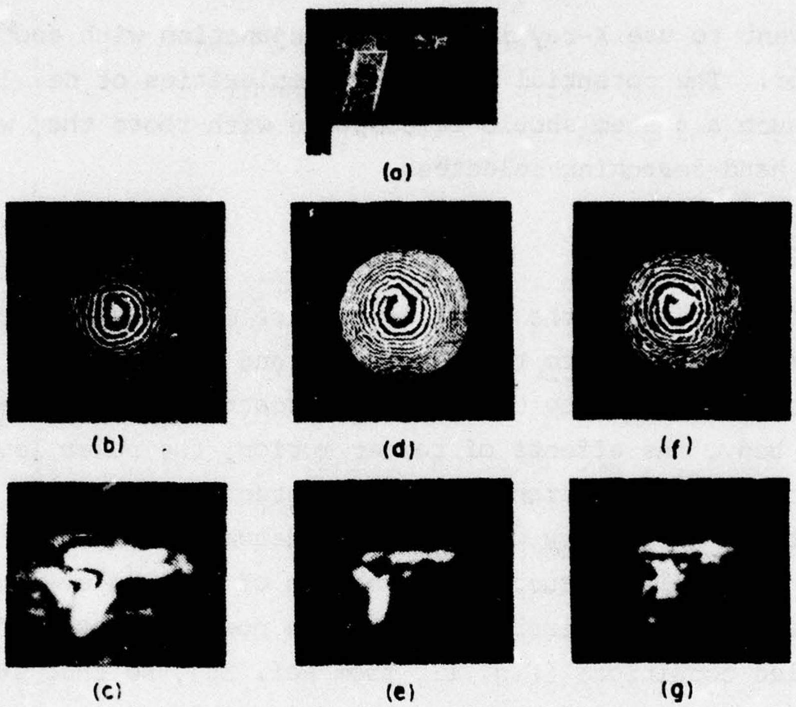

FIGURE 13. Toy Pistol (a), Holograms (b, d, f), and Retrieved Images (c, e, g) (Ref. 55)

In the millimeter-wave and microwave region of the spectrum, where the wavelengths vary from a few centimeters to a few millimeters, the scattering problem is more severe than in the optical region. The poorer resolution at radar wavelengths results in larger portions of the object contributing to each resolution element, and since man-made metallic objects are very smooth relative to millimeter wavelengths (though rough with respect to optical wavelengths), the scattering is highly specular in nature. The strength of the return from each portion of the object is then very sensitive to its orientation to the illuminating beam. Parts of the object which are very significant when viewed at optical wavelengths may often return such little energy at millimeter wavelengths that they do not contribute

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to the resultant image. That is, when the detection system is required to handle the glints, the diffuse returns from other parts of the object may be below the system threshold, so that the image is not "filled in" as an optical image would be. When visually significant portions of the object are below threshold, obvious problems in recognition arise.

A straightforward attack on this problem is to develop systems which are sensitive over wide dynamic range, and which compress the dynamic range on display so that the eye and film can handle it. This is not easily done, and very little effort has been devoted to it.

A second approach is to attempt to reject the glint returns before detection and to work only with the diffuse returns which are limited in dynamic range and which are available from all parts of the object. Preliminary work of this kind has been performed by Farhat at the University of Pennsylvania and Levin, Feingold, and Miller at the RCA Advanced Technology Laboratories in Camden, New Jersey. Farhat uses a holographic technique, whereas the RCA work utilizes a more conventional millimeter-wave lens system. Both have produced recognizable images of handguns under very limited and highly controlled conditions. The rejection of specular reflections may adversely affect the contrast between gun and body reflections. This still requires investigation.

1. Millimeter-Wave Lens System

The research at RCA is representative of what can be done in this area. It is a continuation of work begun by Hofer, Jacobs, and Schumacher (Ref. 56) and is being supported by the U.S. Army Electronics Command at Fort Monmouth, New Jersey. Figure 14 shows the most direct implementation of that system. The target area is illuminated by a small horn. The returns are focused by the lens. The receiving waveguide is scanned across the image plane in synchronism with the cathode-ray tube (CRT) beam and the CRT intensity is modulated by the received signal to convert the millimeter-wave image to an optical image for direct viewing or photographic recording.

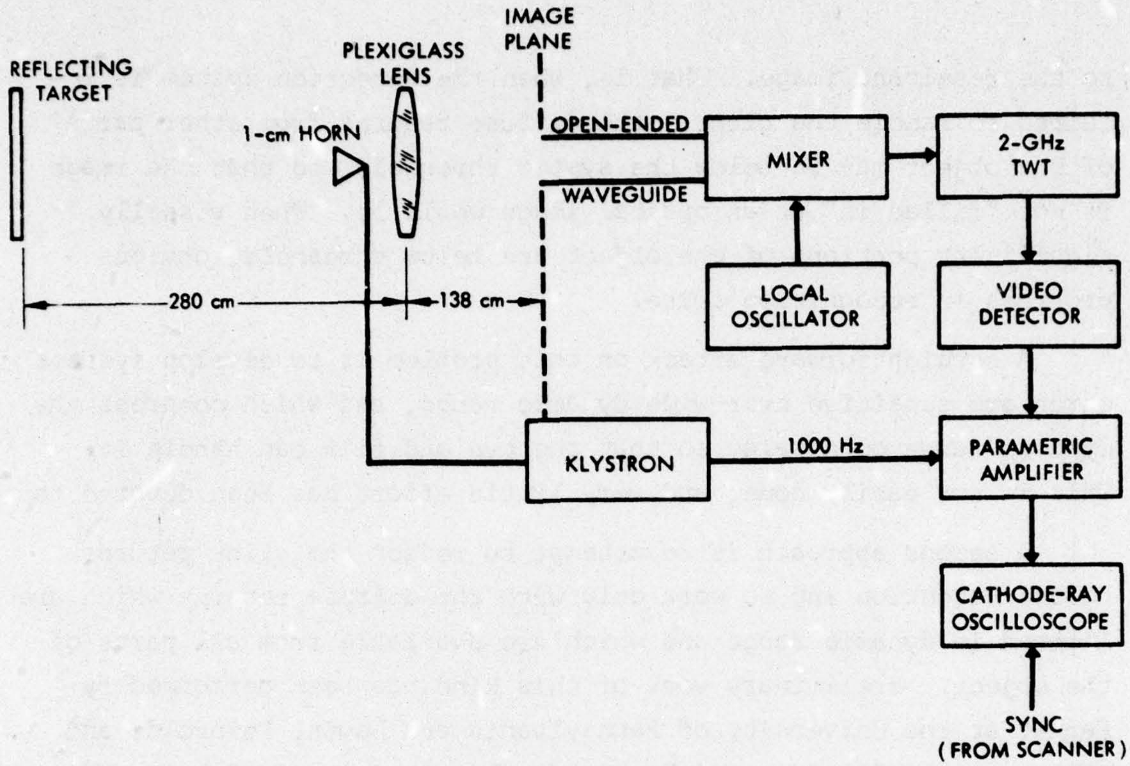

FIGURE 14. Block Diagram of Millimeter-Wave Lens Imaging System (Courtesy of RCA Advanced Technology Laboratories)

The pertinent system parameters are as follows:

Frequency (f) = 94 GHz

Wavelength (λ) = 3.2 mm

Lens Diameter (D) = 500 mm

Angular Resolution (θ) = $1.22 \frac{\lambda}{D}$ = 7.8 mrad

Resolution (at 4 m) = θR = 31 mm

Depth of Field (at 4 m) = 50 cm

Radiated Power = 500 mw

Illuminated Area ~ 1000 cm^2

Power Density at Target ~ 0.5 mw/cm^2

With this system an aluminum-foil-wrapped letter R (15 cm high and 9 cm wide) can be imaged if oriented to reduce, though not eliminate, specular reflections.

The major contribution of the RCA work is to apply techniques of spatial filtering to the problem. As is known from optical theory, the Fourier transform of a uniformly illuminated object placed in front of a converging lens is produced in the back focal plane of the lens (Ref. 57). The amplitude and phase of the illumination at coordinates x,y in the focal plane are related to the Fourier transform of the object scattering at the spatial frequencies $x/\lambda f$, $y/\lambda f$, where f is the focal length of the lens. Thus, low spatial frequencies occur near the optic axis, where $x \sim 0$ and $y \sim 0$, and high spatial frequencies are located away from the optic axis. If the specular scattering by an object has predominant Fourier components in a narrow band and if the diffuse scattering has significant components outside of this band, then spatial filtering in the back focal plane can be used before detection to accentuate different contributions to the return. Careful experiments and analysis are necessary to determine the Fourier spectrum associated with various parts of guns at different orientations. In lieu of this work it is plausible to assume that the specular returns are primarily due to direct retroreflection by smooth, plane surfaces. If this is so, then the backscatter will be in the form of a plane wave along the optic axis, and its spatial frequency will be zero. In fact, the finite size of the scattering surface will cause diffraction effects which introduce higher frequency components. Corners and cavities and resonant elements may produce interference effects which are also specular in nature and which have high-frequency components. Nevertheless, the predominant energy in specular scattering may be concentrated in low-frequency components. The diffuse scattering is expected to reflect energy into a broad range of angles, which implies a broad range of spatial frequency components. As a consequence, a stop in the focal plane, near the optic axis, may strongly attenuate the specular returns while allowing most of the energy

from diffuse reflections to pass. This argument has been made by Levin, Feingold, and Miller, and it provides the foundation for their efforts at image formation.

A further improvement in target scattering characteristics may result if the coherence of the illumination is reduced. One way of doing this is to divide the transmitter power into several channels, say three, and have each channel illuminate the target from a different direction. The angle between any two channels need only be sufficiently large that both are not within the main lobe of any specular glint. For a range of 4 m, it should be adequate to place the secondary channel horns at the perimeter of the lens.

The coherency can be reduced still further by placing variable phase shifters in two of the three channels and varying the phase asynchronously during the observation time. This should effectively eliminate glints which are produced by interference effects.

When the specular returns are rejected, much of the scattered energy is discarded. The system sensitivity must then be high in order to work mainly with the diffuse returns. The strength of the diffuse signal depends upon the diffuse scattering mechanisms, which are not well understood at present for complex objects, and upon the implementation of the detection system. If the illuminating beam of the system discussed above is adjusted to cover uniformly an area of 100 resolution elements at a range of 10 m, and if the diffuse reflectivity is estimated at 0.01, then (without losses) the signal collected by the lens from each resolution cell will be of the order of 10^{-9} watt. If N is the number of resolution elements, a conceptual real-time detection system might entail a factor of N loss due to collection inefficiency and an additional factor of N loss due to time-sharing of a single receiver among N resolution elements. The received power per resolution cell would then be reduced by a factor of N^2 to about 10^{-13} watt. If the entire image is sampled with a frame time of 1/30 sec, then a bandwidth of 3000 Hz is required. With a receiver noise figure of 16 db, the noise power is 5×10^{-16} watt.

the resultant signal-to-noise ratio of 200 provides a margin for system losses and overestimation of the diffuse scattering reflectivity.

The development of a real-time detection system of reasonable cost is another major objective of the work at RCA. The initial work has utilized a germanium semiconductor panel dissector of the kind developed by Jacobs and his colleagues (Refs. 56, 58) at Ft. Monmouth. The transmission of millimeter waves by these panels can be controlled by optical illumination of the semiconductor surface. The development of a pyroelectric array is also being pursued. Characteristics of pyroelectric detectors have been described by Hadni (Ref. 59), Puttey (Ref. 60), and Glass and Abrams (Ref. 61). The sensitivity of these devices is about 10 db below that of conventional point-contact diode detectors at 4-mm wavelengths (Ref. 62).

2. Millimeter-Wave Holography

Holographic techniques provide a powerful tool for the improvement of radar imaging systems. Early work at X-band has been reported by Dooley (Ref. 63). Papers by Leith (Ref. 64), Iizuka (Ref. 65), and Larson, Johansen, and Zelenka (Ref. 66) contain extensive references to other work in microwave holography. Recently, Farhat (Ref. 55) at the Univeristy of Pennsylvania has developed a millimeter-wave system at 70 GHz (λ = 4.3 mm). He recognized that specular glints cause severe degradations in image quality and developed a novel technique to reduce their impact. In his system the signal was hard-limited to remove the amplitude information, and the remaining phase information was used to intensity-modulate a cathode ray tube (CRT). The CRT beam was moved in synchronism with the detecting horn, and a time-exposure photograph of the CRT faceplate produced a film whose density was everywhere proportional to the phase of the radiation scattered by the target. This phase-hologram (when demagnified) served for the reconstruction of the image. The use of phase information alone, which varies from 0 to 2π, substantially reduces the dynamic range requirements of the recording system. It

provides the added advantage of emphasizing the image outlines and thus aiding recognition.

A simplified block diagram of the recording and reconstruction systems is shown in Fig. 15 (Ref. 55). The target area was illuminated by a CW klystron with a power output of 0.75 watt. A relatively uniform power density of 0.2 mw/cm^2 was produced over the object area. The scattered radiation was received by a horn which was scanned over a circular recording aperture 0.75 m in diameter. The klystron was phase-locked to the local oscillator of a coherent receiver, so that the local oscillator provided the necessary reference signal for holographic interference. After mixing and amplification, the IF signal was limited and phase-detected to produce an output voltage which was proportional to the phase of the received radiation. This voltage was then used for intensity modulation of the CRT.

The resulting phase-hologram was demagnified and then illuminated with a spatially filtered and collimated He-Ne laser beam. The lens arrangement shown in Fig. 15b was adjusted to focus a reconstructed real image of the target on the screen. Recognizable images of a metallic toy gun were obtained at distances of 1.25 m and 7 m from the recording aperture. When the gun was placed in the pocket of a tweed coat or a plastic handbag the reduction in signal-to-noise ratio had only a small effect on the image quality.

Farhat is interested in pursuing this work in several directions. These include investigations of:

1. Scattering characteristics of several guns at different orientations
2. Effects of concealment
3. Effects of body backscatter
4. Real-time area detection and real-time reconstruction systems.

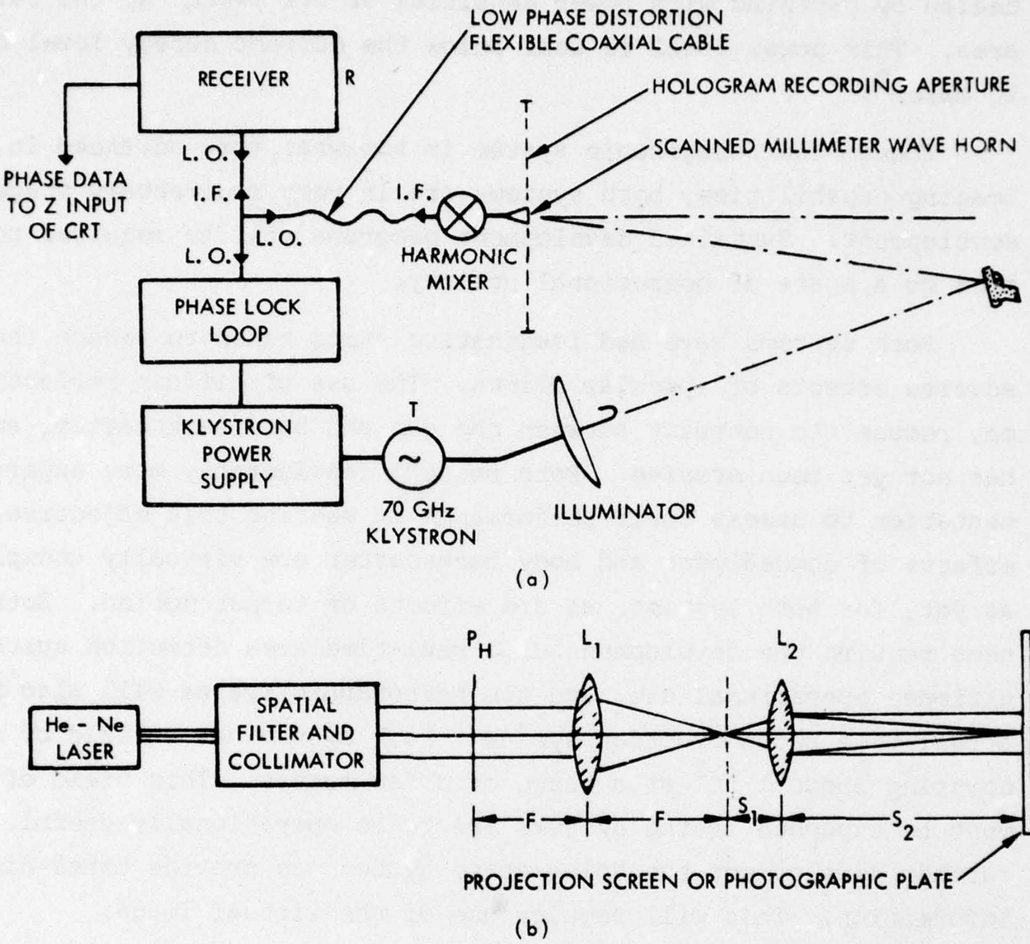

FIGURE 15. Block Diagram of Millimeter-Wave Holographic System (Ref. 55)

He is now working with a very low-priced glow discharge detector, which may serve as the foundation for a real-time imaging detection system. His work is currently being supported entirely from university funds. These are limited and do not provide a basis for rapid advancement in the field.

3. Discussion

Millimeter-wave lens imaging and millimeter-wave holography systems have begun to provide recognizable images of handguns. These

have been obtained at ranges of several meters with the weapon concealed by clothing with power densities of 0.2 mw/cm^2 at the target area. This power level is well below the current safety level of 10 mw/cm^2.

Though the holographic system is somewhat more advanced in its imaging capabilities, both systems are in very rudimentary stages of development. Sustained development programs will be required to bring them to a state of operational utility.

Both systems have had imaginative steps taken to reduce the adverse effects of specular glints. The use of diffuse reflections may reduce the contrast between the gun and body backscatter, and this has not yet been studied. Both require considerably more experimentation to assess their performance in meeting this objective. The effects of concealment and body backscatter are virtually unexplored, as yet, for both systems, as are effects of target motion. Both systems require the development of a real-time area detection system for ultimate operational use, and the holographic system will also need a real-time reconstruction system. Each system has a field of view covering about 1 ft^2 at a range of a few meters. This field of view must be expanded if the systems are to be operationally useful. With further development the holographic system can provide three-dimensional information. This will require use of the virtual image.

4. Conclusions and Recommendations

Determination of the imaging quality of these systems for a greater number of guns in more varied orientations and establishment of the effects of concealment and body backscatter are of first priority in this effort. This work will probably require the development of even more sophisticated filtering techniques than are currently being employed. The effects of small body motions of stationary individuals on the image also need investigation. Some measurements of this kind are being done with the millimeter-wave lens system with Federal Government support. The millimeter-wave holographic system shows considerable promise, and measurements with

this system deserve support. A one-year program should range in cost from $50,000 to $100,000.

If the imaging properties of these systems are shown to be satisfactory, considerable development will be required to obtain systems which survey operationally useful areas in acceptable times. The systems, when developed, will be expensive but probably comparable in cost to X-ray or infrared systems designed for the same application.

F. INFRARED IMAGING

The results of the earlier analysis of the feasibility of detecting concealed weapons with infrared imagery (Ref. 1) were quite pessimistic. However, the scope of the analysis was limited to IR wavelengths of less than 14 microns, where the opaqueness of clothing is high. Recent measurements of Texas Instruments discussed below indicate that the transmittance of clothing is relatively high (roughly 20 to 50 percent) in the wavelength range of a few hundred microns. These measurements, along with recognition that the contribution to the contrast of emissivity differences between a metallic weapon and the human epidermis is likely to be two to three orders of magnitude greater than that due to temperature differences, lead to the conclusion that in the few-hundred-micron range either passive or active IR imagery is feasible conceptually. But in either case a major effort would be required for hardware development.

1. Passive Infrared Detection

The rate of transmission of information in the form of an image and the probability of detecting an object in a scene basically depends on the amount of degradation of the optical signal-to-noise ratio of the image of the object as it is transmitted from the scene to the brain of the user. Thus, in order to discuss the feasibility of an infrared imaging system for detecting concealed weapons it is necessary to consider those factors which affect the optical signal-to-noise ratio. The optical signal is due to the spatially varying part of the mean radiant power per unit area. The noise is due to the

fluctuations in the radiant power per unit area. Fluctuations in the radiance of the output image on the display of an infrared imaging system may be due to electrical noise generated within the image system as well as shot noise arising from the photoelectric detection process itself. It has been determined that the optical signal-to-noise ratio required to detect an object with a 50 percent probability in 0.2-0.3 sec must exceed roughly 3-5 (Ref. 67).

All matter at any finite temperature, no matter how cool it may be, continuously emits and absorbs electromagnetic radiant energy. Emission results from the continual motion of the charged particles which make up matter. Since the thermal motion of the electrons and nuclei increases with temperature, the continuous radiant power from a particular object must increase with temperature.

Electromagnetic waves are radiated over a wide range of wavelengths by these processes. Traditionally, the unit of wavelength in the visible and infrared has been the angstrom equal to 10^{-10} meter and the micron equal to 10^{-6} meter. The wavelength regions of the electromagnetic spectrum are shown in Fig. 16. They include radio waves, microwaves, infrared, visible, ultraviolet, X rays, and gamma rays. The visible region extends approximately from 0.3 to 0.75 micron. The infrared extends from the red limit of the visible at approximately 0.75 micron to approximately 1000 microns where microwave techniques to produce and detect signals can be employed.

The quantitative information required to deduce an accurate image of a man with a concealed weapon employing thermal infrared radiation is far from complete, although the method of analysis is quite well in hand. A large number of factors must be considered:

- The spectral content of the radiant power emitted by the scene.
- The spatial variation in emission of radiant power by targets (concealed weapons) and backgrounds (human skin, clothes, etc.) to form the optical signal to be detected with the aid of an infrared system.

- The attenuation of the optical signal by absorption and scattering of radiant power by the intervening media (primarily clothing in this case) between the subject and the infrared system.
- The attenuation of the optical signal by the optical objective of the infrared imaging system.
- The conversion of the optical signal into an electrical signal and the generation of electrical noise by the infrared system.
- The conversion of the electrical signal into a luminous reproduction of the original scene on the display.

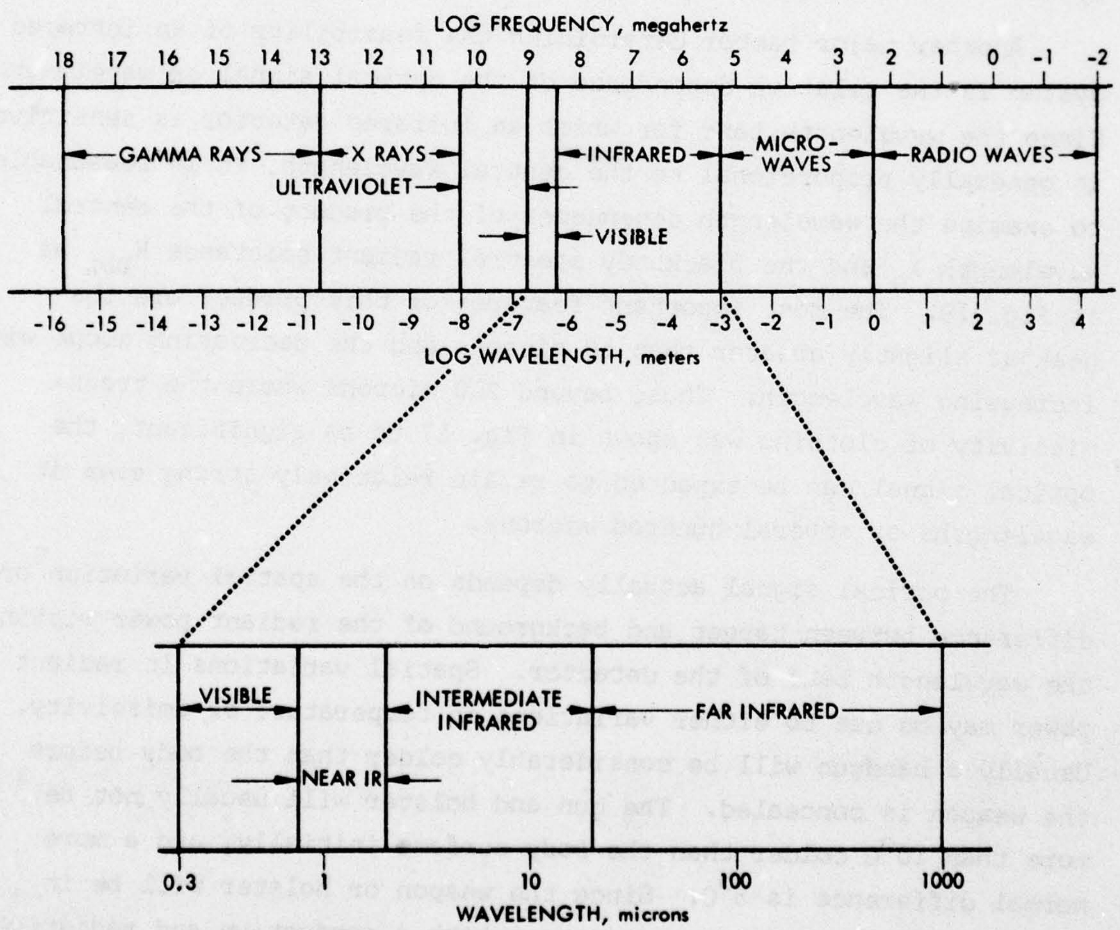

FIGURE 16. The Electromagnetic Spectrum

A major factor determining the feasibility of an infrared system for detection of concealed weapons is the attenuation of the optical signal by clothing. The transmittance of clothing and corrugated cardboard is shown in Fig. 17 (Ref. 68). Accuracy of the data was stated to be about 3 percent. The most significant feature of the data is the rapid increase in transmittance with wavelength λ beyond 200 microns. All the suit materials show transmittances approaching 40 to 50 percent at 500 microns. Even heavy overcoat material has a transmittance of about 15 percent. Cardboard which might be used to conceal a weapon has a 40 percent transmittance. These results indicate that the most favorable wavelength region for an infrared imaging system is at wavelengths greater than 200 microns.

Another major factor determining the feasibility of an infrared system is the relative dependence of the optical signal or wavelength. Since the wavelength band for which an infrared detector is sensitive is generally proportional to the central wavelength, it is reasonable to examine the wavelength dependence of the product of the central wavelength λ_o and the blackbody spectral radiant emittance $R_{bb\lambda}$ as in Fig. 18. The most important features of this product are the peak at slightly greater than 10 microns and the decreasing slope with increasing wavelength. Thus, beyond 200 microns where the transmissivity of clothing was shown in Fig. 17 to be significant, the optical signal can be expected to remain relatively strong even at wavelengths of several hundred microns.

The optical signal actually depends on the spatial variation or difference between target and background of the radiant power within the wavelength band of the detector. Spatial variations in radiant power may be due to either variations in temperature or emissivity. Usually a handgun will be considerably colder than the body before the weapon is concealed. The gun and holster will usually not be more than 10^oC colder than the body surface initially, and a more normal difference is 5^oC. Since the weapon or holster will be in contact with the body, we may expect both a conductive and radiative

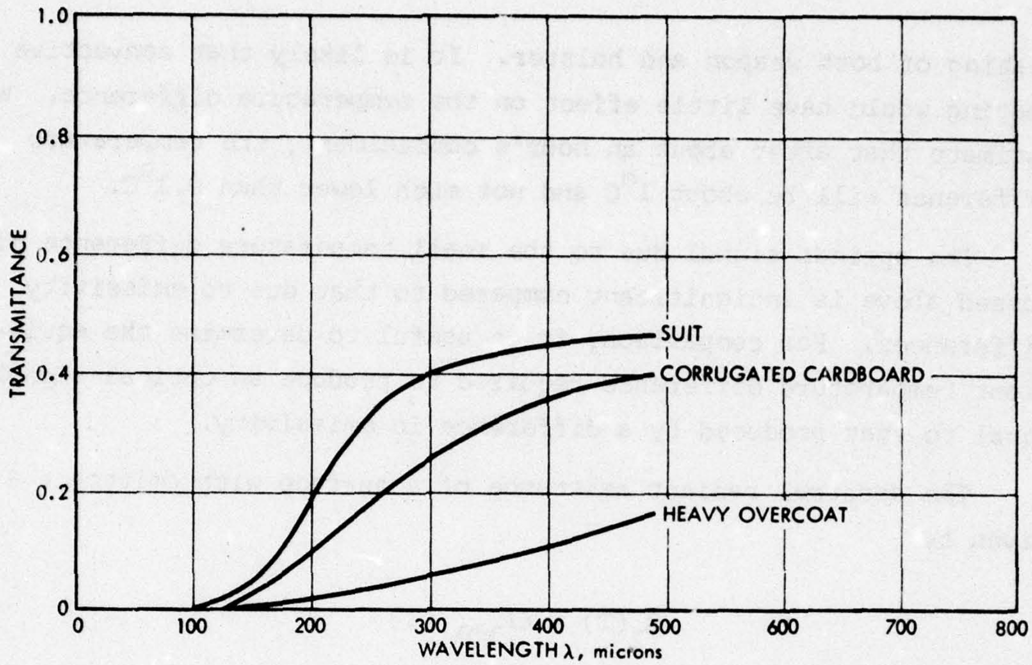

FIGURE 17. Transmittance Versus Wavelength

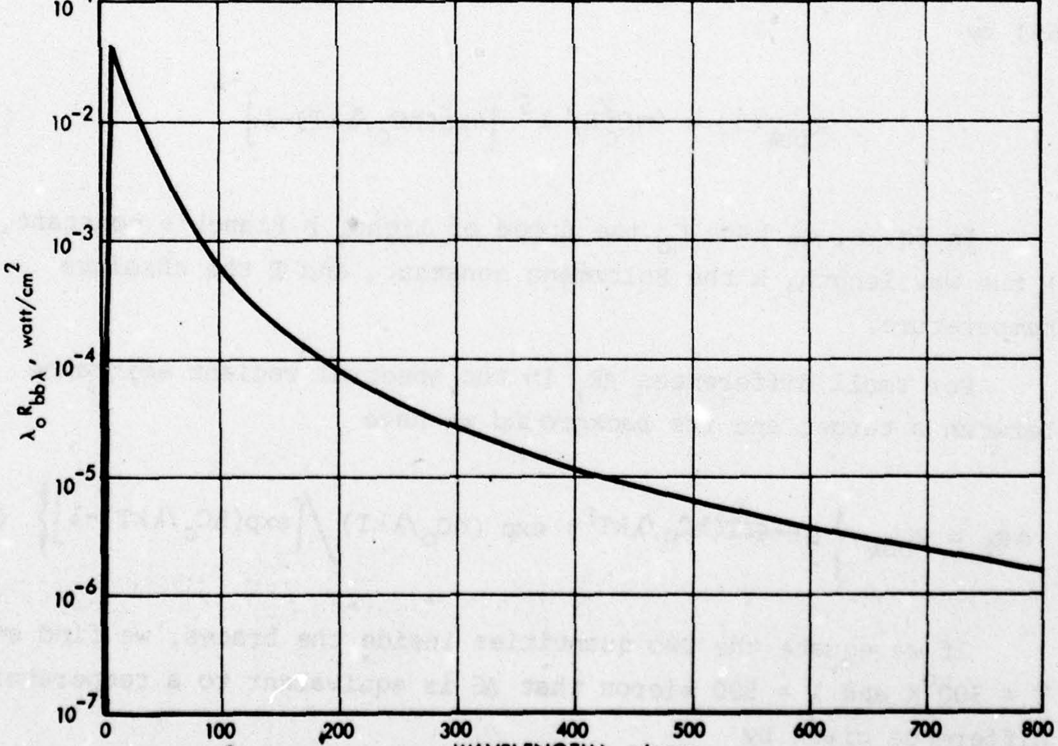

FIGURE 18. Product of Detector Central Wavelength λ_o and Blackbody Spectral Radiance Versus Wavelength

heating of both weapon and holster. It is likely that convective heating would have little effect on the temperature difference. We estimate that after about an hour's concealment, the temperature difference will be about $1^{o}C$ and not much lower than $0.1^{o}C$.

The optical signal due to the small temperature difference discussed above is insignificant compared to that due to emissivity differences. For comparison, it is useful to determine the equivalent temperature difference required to produce an optical signal equal to that produced by a difference in emissivity.

The spectral radiant emittance of a surface with emittance ϵ is given by

$$R_{\lambda}(T) = \epsilon R_{bb\lambda}(T) \tag{7}$$

where the blackbody spectral radiant emittance $R_{bb\lambda}$ is given (Ref. 69) by

$$R_{bb\lambda}(T) = 2\pi C_{o}^{2}h/\lambda^{5}\left[\exp(hC_{o}/\lambda kT)-1\right]^{-1} \tag{8}$$

In Eq. 8, we have C_o the speed of light, h Planck's constant, λ the wavelength, k the Boltzmann constant, and T the absolute temperature.

For small differences ΔR_{λ} in the spectral radiant emittance between a target and its background we have

$$\Delta R_{\lambda} = R_{bb\lambda}\left\{\Delta\epsilon+\epsilon\Delta T(hC_{o}/\lambda kT^{2})\exp(hC_{o}/\lambda kT)\Big/\left[\exp(hC_{o}/\lambda kT)-1\right]\right\} \tag{9}$$

If we equate the two quantities inside the braces, we find at $T = 300^{o}K$ and $\lambda = 500$ micron that $\Delta\epsilon$ is equivalent to a temperature difference given by

$$\Delta T = 312 \; \Delta\epsilon/\epsilon \tag{10}$$

While the exact value of the difference in emissivities of a weapon and human skin at λ = 500 micron is not available, from our knowledge of the physics of the emissivity of materials and from extrapolation from shorter wavelengths we can be sure the difference will be large. The emissivity of metallic surfaces such as steel is only 4 percent at 14 microns (Ref. 69, p. 77) and probably even lower at 500 micron. On the other hand, human skin is essentially a black-body emitter with unity emissivity at wavelengths greater than 6 microns (Ref. 70). A conservative estimate for $\Delta\epsilon$ would be 0.5 which is equivalent to a temperature difference of about 156°C, compared to the actual temperature difference 0.1-1°C predicted above. Thus, the optical signal due to the emissivity difference will be two to three orders of magnitude greater than that due to the actual temperature difference.

The radiant emittance of clothing itself, provided that spatial variations in the vicinity of the concealed weapon are small as expected, will not contribute to the optical signal, which is proportional to radiant emmitance differences. The only effect of clothing is to attenuate the optical signal in proportion to the transmittance of the clothing.

The potential usefulness of an infrared imaging system for detecting a concealed weapon can be estimated by the number of periods of the resolution frequency in the object plane equal to the width of the weapon. It has been shown that, to detect a low-contrast target, the width of the target must be at least equal to one period of the resolution frequency. The resolution frequency is determined in principle with sine-wave, spatially modulated, radiant test patterns. In practice, the resolution frequency is deduced from measurements with square-wave modulated test patterns.

To the approximation that the response of an infrared imaging system is linear and is temporally and spatially invariant, the

modulation (i.e., the ratio of the amplitude of the sine-wave variation in luminance to the mean luminance of the display) on the display is linearly related to the modulation in the scene by the modulation transfer function (MTF). If the modulation M_D on the display and the noise-equivalent modulation (NEM) (i.e., the modulation on the display such that the amplitude of the sine-wave modulated luminance equals the root-mean-square value of the fluctuations in the luminance) are plotted as a function of spatial frequency ν, then the resolution is the frequency determined by the intersection of the two curves. Thus, to determine the resolution of an infrared system we need the MTF and the NEM function. For this purpose, we shall consider the infrared imaging system proposed by Texas Instruments (Ref. 68) and modeled after their Thermiscope, a medical thermograph.

The MTF of an infrared system is determined by the optical objective, the IR detector, the amplifier, and the display. The MTF of the diffraction-limited optical objective referred to the object plane is given by

$$T_o(\nu) = (1/\pi)\,(2\beta - \sin 2\beta) \tag{11}$$

where

$$\beta = \cos^{-1} (\lambda \nu S/D) \tag{12}$$

and λ is the infrared wavelength in millimeter, ν is the spatial frequency in cycle/mm, S is the object distance, and D is the diameter of the aperture. For the system proposed by Texas Instruments (TI) the diameter of the aperture is 300 mm and the object distance 3,000 mm. Thus, β at λ equal 500 microns or 0.5 mm is given by

$$\beta = \cos^{-1} (5\,\nu) \tag{13}$$

The diffraction-limited MTF, $T_o(\nu)$, of this optical objective is shown in Fig. 19.

The MTF of an IR detector is given by

$$T_d(\nu) = (\sin \pi\nu w)/\pi\nu w \qquad (14)$$

where w is the width of the detector in millimeter. TI suggested a detector 2 mm square at λ = 500 microns, and thus the modulation transfer function referred to the object plane is as shown in Fig. 19.

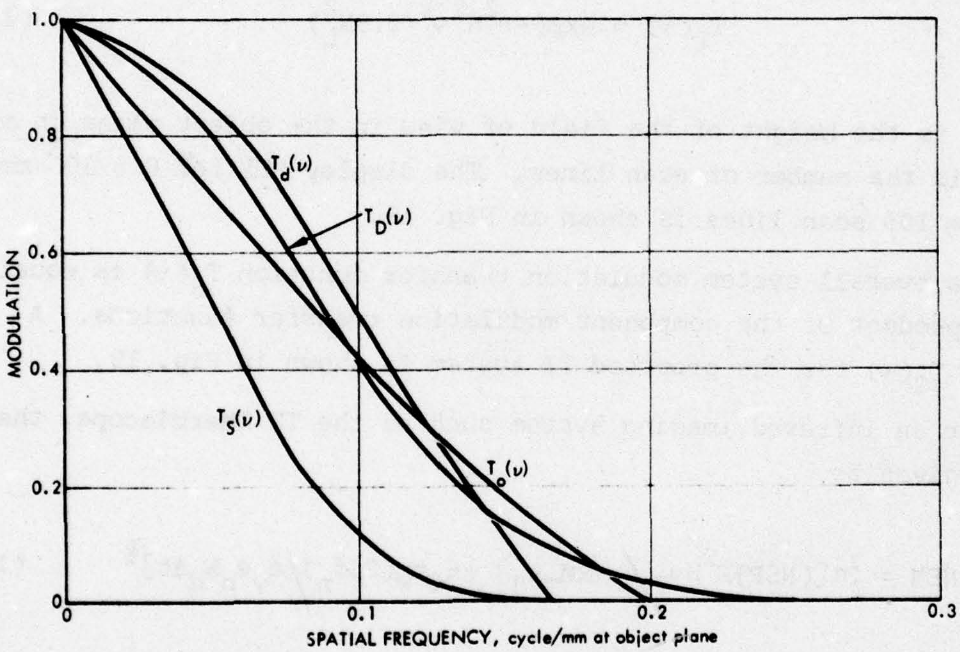

FIGURE 19. Modulation Transfer Functions Versus Spatial Frequency Referred to Object Plane. $T_D(\upsilon)$ is Display MTF, $T_d(\upsilon)$ is IR Detector MTF, $T_o(\upsilon)$ is Optical Objective MTF, and $T_S(\upsilon)$ is System MTF

Generally amplifiers can be built with sufficient frequency response that their effect on the system MTF is negligible.

The MTF of the display is determined by the desirability of obtaining a flat luminance field without noticeable scan lines.

The spacing between scan lines referred to the object plane is chosen approximately equal to the height of a detector (6 mm at the object plane). Thus, for a field of view equal to approximately 10^3 mm in height, TI has chosen 195 scan lines corresponding to a spacing of approximately 5 mm. In order to obtain a flat luminance field on a cathode ray tube display with the Gaussian spot formed by the electron beam, adjacent scan lines ought to overlap at approximately the 50 percent points. The result is an approximate display modulation transfer function referred to the object plane given by

$$T_D(\nu) = \exp(-\pi^2 H^2 \nu^2 / 2.8 N_L^2) \tag{15}$$

where H is the height of the field of view in the object plane in mm and N_L is the number of scan lines. The display MTF for $H = 10^3$ mm and $N_L = 195$ scan lines is shown in Fig. 19.

The overall system modulation transfer function $T_S(\nu)$ is equal to the product of the component modulation transfer functions. A plot of $T_S(\nu)$ for the proposed TI system is shown in Fig. 19.

For an infrared imaging system such as the TI Thermiscope, the NEM is given by

$$\mathrm{NEM} = 2\pi[(\mathrm{NEP})F^2 W\nu_o / \tau \mathrm{TRM}_T A_d]\,[\epsilon_d t_w (2\Delta f_n) / e_v e_h N_d \Delta t]^{\frac{1}{2}} \tag{16}$$

where

NEP is the noise-equivalent power of the IR detector

F is the f/number of the optical objective

ν_o is the spatial frequency of the sine-wave test pattern on the display

W is the width of the display

τ is the transmittance of clothing

η is the transmittance of the optical objective

R is the mean radiance of the scene within the spectral bandwidth of the IR detector

M_T is the modulation of the test pattern

A_d is the area of the detector

ϵ_d is the height-to-width ratio of the display

t_w is the time required to scan across a half-period of the test pattern

Δf_n is the noise bandwidth

e_v, e_h are the vertical and horizontal scan efficiencies

N_d is the number of IR detectors

Δt is the integration time, equal to the greater of the frame time t_F and eye integration time

The eye integration time is approximately 0.2 seconds, and t_F is given by

$$t_F = N_L/6e_v \omega N_d, \tag{17}$$

where ω is the rotational velocity of the six-sided scan mirror.

The factor t_w is related to system parameters by the equation

$$t_w = e_h/12\omega W \nu_o, \tag{18}$$

where the factors are as defined above.

The noise bandwidth is given by

$$2\Delta f_n = \int_{\infty}^{\infty} T_D^2(f) T_w^2(f) dt \tag{19}$$

where $T_D(f)$ is the display modulation transfer function (we assume the contribution of the amplifier response to the modulation transfer function is negligible), f is the video frequency corresponding to a spatial frequency ν, and $T_w(f)$ is an expression in frequency space of the fact that the eye integrates the luminous flux over a half-period of the sine wave test pattern. The parameters f and ν are related by

$$f = 6RW\nu/e_h \tag{20}$$

and $T_w(f)$ is given by

$$T_w(f) = \sin \pi f t_w / \pi f t_w$$

The assumed values of the parameters required to calculate the noise equivalent modulation with Eq. 16 are shown in Table 16. The value of the background radiance R is that of a blackbody radiator (the human skin) within a spectral bandwidth equal to approximately one-third the central wavelength (Fig. 18) at 500 microns.

TABLE 16. ASSUMED VALUES OF PARAMETERS

NEP	10^{-12} watt/$Hz^{1/2}$	N_d	1	N_L	195
F	2.5	M_T	0.5	e_v	0.8
τ	0.5	A_d	4 mm^2	e_h	0.095
η	0.9	ϵ_d	3/4	ω	13.5 rps
R	2×10^{-6} watt/cm^2	t_w	2.4 sec		

An indium antimonide detector with NEP equal to 10^{-12}-10^{-13} watt/$Hz^{1/2}$ is available at λ = 500 micron. The value of M_T = 0.5 was chosen to correspond to the difference in emissivity of a weapon and human skin discussed above. The system parameters correspond to the

values proposed by TI. The result of the calculation of NEM is shown in Fig. 20 along with the modulation on the display M_D for the assumed test pattern modulation as a function of spatial frequency referred to the object plane. From the intersection of the M_D and NEM curves we find the resolution is approximately 0.094 cycle/mm. The minimum width of an object detectable with the system would be approximately 1.0 cm or 0.4 in. Since the dimensions of a handgun are several times larger than 0.4 in., the weapon would be readily detected and recognized by its shape.

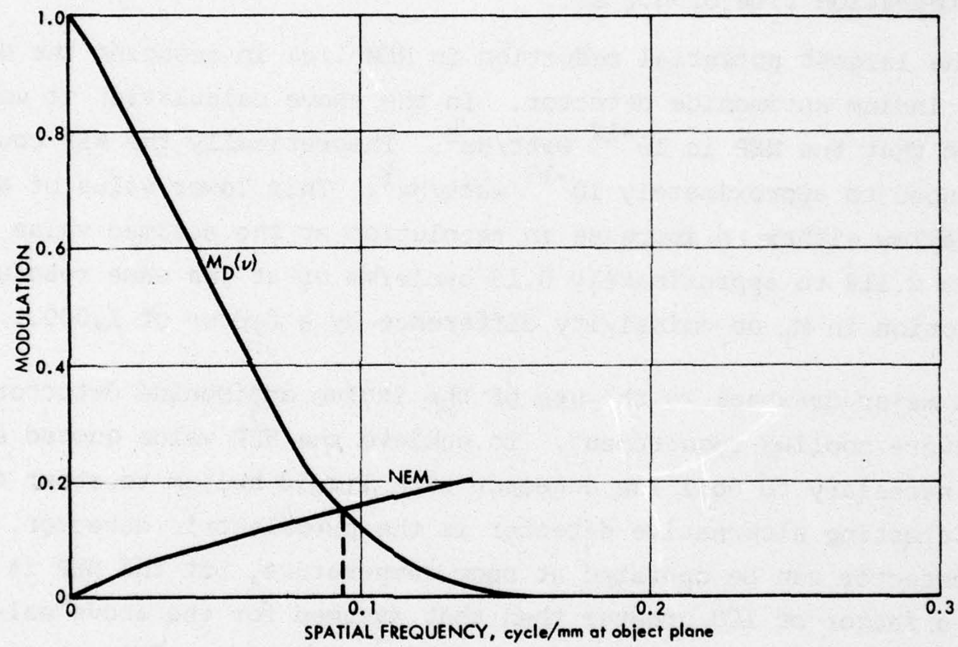

FIGURE 20. Modulation Versus Spatial Frequency Referred to Object Plane. $M_D(\nu)$ is Modulation on Display and NEM is Noise-Equivalent Modulation on Display. Note Resolution Frequency Indicated by Dashed Line

Some improvement in resolution could be accomplished by increasing the MTF through choice of a smaller detector and more scan lines, which would allow use of a smaller electron beam spot size on the display. However, significant improvement (a factor of two) in the resolution

cannot be achieved in this way without improving the MTF by enlarging the aperture of the optical objective.

The resolution could also be increased by reducing the NEM either by employing more than one detector or by improving (reducing) the NEP of the detector. However, rather than reduce NEM by employing more detectors it would seem advisable to employ more detectors to reduce the frame time. According to Eq. 17 the frame time of the proposed system is 2.4 sec. By employing 20 detectors the frame time would be reduced to 0.12 sec and the integration time Δt would decrease to the eye integration time of 0.2 sec.

The largest potential reduction in NEM lies in reducing the NEP of the indium antimonide detector. In the above calculation it was assumed that the NEP is 10^{-12} watt/Hz$^{\frac{1}{2}}$. Theoretically the NEP could be reduced to approximately 10^{-15} watt/Hz$^{\frac{1}{2}}$. This lower value of NEP would allow either an increase in resolution at the assumed value of M_T from 0.114 to approximately 0.15 cycle/mm or at the same resolution a reduction in M_T or emissivity difference by a factor of 1,000.

A major drawback to the use of the indium antimonide detector is the severe cooling requirement. To achieve the NEP value quoted above, it is necessary to cool the detector with liquid helium to about 4.2°K. An interesting alternative detector is the pyroelectric detector. This detector can be operated at room temperature, but the NEP is about a factor of 100 greater than that assumed for the above calculation of resolution. In order to offset the higher NEP, it is clear from Eq. 16 that it would be necessary to employ an active source of radiant power to increase the apparent radiance of the scene by a factor of 100.

2. Active Infrared Detection

The above theoretical prediction of the resolution was based on our estimate of 0.5 for the emissivity difference between a metallic weapon and the human epidermis. Even though this estimate is conservative, the apparent radiance difference and hence modulation may not

be as correspondingly large. Materials of low emissivity, such as a metallic weapon, possess high reflectivity and thus reflect a high proportion of the radiant power incident on them from the surroundings. However, the high emissivity and reflectivity differences can be exploited fully by employing an active source of radiant power of sufficient magnitude that the power reflected by a metallic object exceeds the passive radiance of the skin. The radiance of the skin listed in Table 16 is approximately 2×10^{-6} watt/cm^2 within the bandwidth of the detector. If the area irradiated by the source is to be about one square meter, then a source power of about 20 milliwatts would be required.

Several experimental sources of radiant power at several hundred micrometer wavelength have been built. However, considerable development work would be required to obtain a practical, compact, efficient source suitable for system applications.

The experimental sources include a backward wave oscillator (carcinotron), several gas lasers, a tunable stimulated Raman laser, and the mixing of two visible or near-infrared laser signals in a nonlinear crystal to obtain the difference frequency at several hundred micrometers. The carcinotron produces a few milliwatts at wavelengths as short as 1000 micrometers, but the power efficiency is low and the bulky power supply is a severe requirement. Gas lasers in the hundred-micrometer range include HCN, H_2O, D_2O, DCN, SO_2, CH_3F, CH_3CN and CH_3CCH. The HCN gas laser is currently the most powerful source, yielding from 10 to several hundred milliwatts CW, depending on the length of the tube, at 311 and 337 micrometers. A major drawback to any gas laser is the tendency to be quite large. A tube 1 meter in length is required to obtain roughly 10 milliwatts. From 100 to 200 milliwatts CW have been reported for a 3-meter tube. The most powerful HCN laser reported so far yielded 600 milliwatts CW with an 8-meter tube. Although only 20 milliwatts CW are needed with the indium antimonide detector, a more powerful source would ease the requirement on detector NEP and concomitantly on cooling. A 2-watt source would

permit the use of the room-temperature pyroelectric detector. Engineering development could result in considerable reduction in the current tube length for a given output power.

3. <u>Program Recommendations</u>

The following study program extending over a period of one year at a cost of approximately $100,000 is recommended:

1. More measurements of the spectral transmittance of clothing in the 100-1000 micron wavelength range with the aim of determining the feasibility of operation at less than 500 microns to achieve higher resolution.

2. Measurements of the emissivity of weapons and human epidermis in the 100-1000 micron wavelength range to establish experimentally the required sensitivity of the infrared system.

3. Laboratory evaluation of the performance of single IR detectors and laser-detector combinations to determine the potential performance (resolution, sensitivity) of passive and infrared imaging systems.

4. Design studies based on the results of the above measurements.

The purpose of this study program would be to establish a practical base for selection of the optimum system design to maximize performance and minimize cost, development time, and risk.

IV. NONLETHAL ANTI-SKYJACKING WEAPONS

A. INTRODUCTION

This section discusses nonlethal weapons possibly appropriate for use by airliner crews or skymarshals against hijackers.

The ideal nonlethal weapon gives instantaneous, controlled, benign, and selective incapacitation. Such a weapon has for centuries been sought in vain. Given the variability of people, circumstances in which a particular nonlethal weapon may have to be used, and marksmanship, the instant knockout is incompatible with the demand for perfect safety.

Nonlethal weapons can be classified into five categories and a miscellaneous group:

1. Chemical
2. Electrical
3. Kinetic energy
4. Systemic drugs
5. Light emission, acoustical, and heat or cold
6. Miscellaneous

We shall discuss candidate chemical weapons and a candidate electrical weapon below. Kinetic-energy weapons are intended to administer a physical blow to immobilize or incapacitate. Examples include sticks and clubs, stun guns firing bags filled with shot, and a variety of guns firing rounds of wood, plastic, rubber, aluminum, grease, or water. These weapons are more suitable for crowd control than for subduing an armed hijacker. Systemic drug weapons, such as a dart gun, fire drug-filled syringe projectiles that immobilize the victim after several minutes' delay. This delay raises serious

doubts about the usefulness of these weapons against a hijacker. Such weapons as high-intensity lights, powerful sounds, stench, cold brine slugs, and heat guns would all, except the last two, cause as much distress to the passengers as to the hijacker. The use of cold or heat would appear to be impractical. Miscellaneous weapons such as marking devices, smoke, foam generators, and weapons creating a slippery footing (e.g., "instant banana peel," low-friction polymers, and liquids) would affect crew, passengers, and hijacker alike.

Three candidates may approach the ideal nonlethal weapon characteristics in the controlled environment of an airliner. They are tear gas, Mace, and pulsed electric currents. Even these have some obvious limitations.

B. TEAR GAS

The mere use of the word "gas" evokes an emotional reaction all out of proportion to the relatively nontoxic effects (less toxic than gasoline or household cleaners) of tear-gas chemicals. This is a propaganda-induced conditioned response. Whether it can be neutralized by counterpropaganda is beyond the scope of this paper, but it should be understood that these agents have far greater safety factors than a multitude, if not a majority, of the commonly used medicines. While some 6000 tons of tear gases were used in World War I, Prentiss (Ref. 71) lists the casualties as zero. The underlying reason for this nonlethality is that in open air lethal concentrations are effectively impossible to maintain. The same is true for CO_2 outdoors and for gasoline fumes in an open filling station.

Empirically, World War I data fit the following equation:

$$\text{Fraction of casualties dying} \approx \frac{1}{(\text{safety factor})^2}$$

where the safety factor is the ratio of lethal to incapacitating doses.

Since this safety factor is about 1000 for tear agents (or "riot" agents), the predicted lethality is very low for concentrations near their tearing threshold (Table 17).

However, tear gas is uniquely safer when employed in an airplane than in combat because (a) oxygen masks are available for all occupants and (b) the concentration can be carefully controlled. Tear gas is only hazardous when breathed in large quantities, and so a person breathing through an oxygen mask in a tear-gas atmosphere is affected only if he opens his eyes. Furthermore, the gas concentration is not subject to the radical variations characteristic of wind-driven clouds from point sources. Chloroform has a very low safety factor (four) but was useful because it was given to the patient in carefully controlled doses.

While the above scenario appears safe on these criteria, it also leaves the hijacker free of the choking harassment from inhaling irritating smokes like CS and CN. He may be forced to close his eyes, but his other faculties will be completely functional. He could pull a trigger or wield a knife, but, being more or less blinded, he would be no match for someone wearing goggles. Instant incapacitation to the point of preventing the shooting or stabbing of a closely held hostage is not possible by gas or aerosol attack. Further, some passengers in the cabin might be adversely affected if they did not use their oxygen masks soon enough, whether through fright, ignorance, or confusion. Infants and the elderly might suffer alarming, if not life-threatening, reactions. Concern for subsequent legal actions on behalf of passengers may also severely restrict application of tear gas.

C. CHEMICAL SPRAYS

Mace can produce almost instantaneous, temporary blindness accompanied by considerable shock and harassment, but a Maced hijacker could still fire a gun or wield a knife, although hit squarely in the face, unable to see, and highly distracted. This gain in suddenness of incapacitation onset is dependent on precision and surprise delivery. The Mace projector would have to be kept concealed while

TABLE 17. THRESHOLD, INTOLERABLE, AND LETHAL CONCENTRATIONS* AND SAFETY FACTORS OF CHEMICAL AGENTS, 1-MIN EXPOSURE (Refs. 71-73)

Agent	Threshold Concentration, mg/m^3 Prentiss	Threshold Concentration, mg/m^3 Wachtel	Threshold Concentration, mg/m^3 Swearengen	Intolerable Concentration, mg/m^3 Prentiss	Intolerable Concentration, mg/m^3 Wachtel	Intolerable Concentration, mg/m^3 Swearengen	Lethal Concentration, mg/m^3	Safety Factor
EBA	3	0.3	3	40	40	40	23,000	600
Chloracetone	18	18	18	100	100	100	23,000	230
Xylyl Bromide	1.8	3.8	1.8	15	56	15	56,000	1,000-4,000
Bromacetone	1.5	1.5	1.5	10	48	10	32,000	670-3,200
Iodoacetone	12	18	--	--	110	--	19,000	1,800
Ethyliodoacetate	1.4	3.5	1.4	15	33	15	15,000	500-1,000
CN	0.3	0.3	0.3	4.5	4.5	4.5	~11,000**	~2,400
CA	0.3	0.3	0.3	0.8	30***	0.8	4,000	~120
DC	0.1	0.2	0.1	0.25	1 2.5 (in a few secs)	0.25	10,000	10,000
DA	0.5	1 (in a few secs)	0.5	1.2	2	1.2	15,000	7,000
DM	0.4	--	0.4	>1.2	>2	22**	30,000	~1,500-10,000
CS	--	--	0.1-0.5	--	--	2-5	~100,000	~20,000-50,000

*Haber's law holds for these chemicals with reasonable accuracy. Therefore, concentration ~1/time for any degree of effect.

**From Military and Chemical Agents, TM 3-215, 1963. Older value for CN in Prentiss slightly smaller (8,500 mg-min/m^3).

***From Stephen Rose, Chemical and Biological Warfare. There is great variability in CA effective dosages and LD_{50} values.

brought within range and then carefully aimed. This weapon, like tear gas, is a good means of overpowering a hijacker who is not prepared to blindly murder a hostage before being captured and might be a useful addition to the crew or skymarshal arsenal.

D. ELECTRIC SHOCK

Instant trigger-finger nerve blockage by pulsed, high-voltage electric shocks is claimed for the Taser weapon system (Ref. 74). The Taser concept is to fire trailing-wire darts into the victim's clothing or skin and then apply 30-kev, 10-microsecond pulses at a rate of 10 per second until the victim is captured. The instantaneous current would be approximately 1 ampere, the average current being 10^{-4} amperes. Figure 21 shows the Taser in pistol and flashlight configurations.

The basic physiological approach is not to electrocute the person to render him incapacitated, but to directly disrupt the nervous system controlling the voluntary muscles. This is, in effect, an interrupted "no-let-go" current applied in 0.1-second intervals, which are too short for the victim to react with a deliberate muscular action such as pulling a trigger. When the pulse train is turned off, the victim immediately recovers and regains his ability to stand, talk, and see.

The advantages of the Taser concept appear to be:

1. Instantaneous incapacitation.
2. Apparently relatively safe against healthy individuals.
3. Precisely controlled range (length of wire).
4. Precisely controlled duration of effect (until switch on projector is turned off).
5. Quickly neutralized if wrong person is hit (turn off power).
6. Multishot.
7. Controllable power levels.
8. Either a one-wire (cabin-grounded) or two-wire system are options.

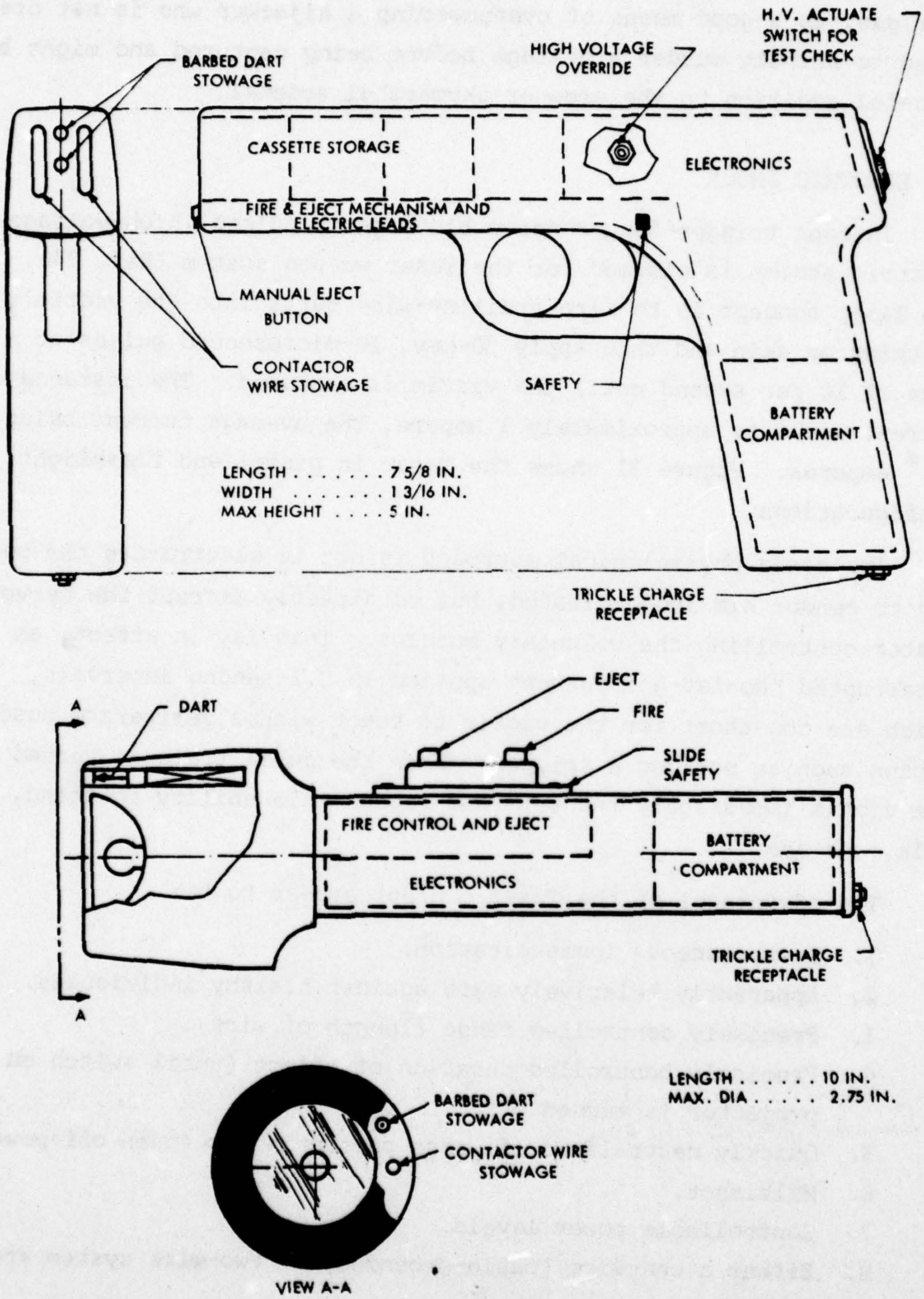

FIGURE 21. Taser in Pistol and Flashlight Configurations (Ref. 74)

9. Small, concealable projectors (pistol or flashlight size and appearance).

The disadvantages are:

1. Possible and unknown chance of deaths from heart fibrillation.
2. Need for marksmanship.
3. Need for actually pointing a device at the hijacker at close range.
4. Public fear of electrocution.

The threshold for heart fibrillation is given as 100-300 ma at 60 cycles for 1-second duration (Ref. 75). The threshold is higher for other frequencies, but the Taser delivers a pulsed square wave of low duty cycle and is not directly comparable. It does not, therefore, follow that the average Taser current of 0.1 ma enjoys a safety factor of 1000 to 3000. Movies of two test individuals show such an overwhelming muscular collapse to Taser pulses that intuitively one fears permanent damage. Certainly, elaborate safety tests of the type used at Edgewood Arsenal for chemical agents are in order.

E. DISCUSSION

Although the topic is nonlethal weapons, realistic scenarios show that hijacking almost always invokes lethal hazards, and the real problem is to prevent either single or mass murder by incapacitating the hijacker before he can take fatal action. If it is a life-and-death requirement to paralyze his weapon hand, the hijacker can be collapsed with high-voltage electrical pulses, provided that the Taser projector can be brought within range, aimed, and fired before the hijacker reacts. Mace is not as incapaciting as the Taser, but it is equally fast, and it is also subject to projector range and aiming limitations. It could be most effective if employed at close range by a well-trained crew member or skymarshal in a situation where the hijacker has no access to lethal force.

For each of these weapons there is an obvious requirement to train personnel in their proper use and in how to deal with passengers who may inadvertently suffer their effects.

F. RECOMMENDATIONS

In view of the foregoing discussion, it is recommended that:

- The Taser electric shock weapon be thoroughly tested as to hazard, effectiveness, and operational utility in providing an instantaneous knockdown capability.
- Range and aiming characteristics of the Taser weapon be measured. If the Taser proves accurate, it could serve as an alternative to the gun in knockdown power.
- Mace could serve as a further option. There is little need for further research and development on Mace.

V. RECAPITULATION, FINDINGS, AND RECOMMENDATIONS

In this final section we bring together and summarize the findings of the previous sections so that a comparison and appraisal can be made.

A. RECAPITULATION

Screening techniques for detection of weapons and explosives can be divided into two categories: imaging and nonimaging. Imaging techniques have low false-alarm rates but require an observer; the reverse is true for most nonimaging techniques. Not all the detection techniques surveyed in Sections II and III show promise. Some were included in our survey because they had been proffered as possible aids in the anti-hijacking and bomb detection problem. Some of the techniques which offer, at present, no prospect for utility in the aircraft protection context are physiological observations, mass detection, conventional television, magnetic imaging, and ultrasonic imaging. A short recapitulation of the promising techniques follows.

1. Dogs

Dogs have demonstrated a capability to detect the presence of explosives (and marijuana) under many circumstances. Little is known about their capabilities to detect concealed weapons. The sensitivity of dogs to explosives' vapors is unknown as is the best way to train dogs for explosives detection. The use of dogs in the detection of explosives has at least limited possibilities and is the most sensitive technique immediately available. Further research concerning dogs' capabilities in this regard could lead to useful results despite the continual support and reinforcement dogs require.

2. Microwave and Millimeter-Wave Techniques

a. Radar. Difficulty in distinguishing the backscatter from weapons, the human body, and metallic clutter carried on the person remains a formidable problem. No information has been found to suggest that nonimaging radar will be useful to detect weapons.

b. Radiometry. This technique is not capable of distinguishing handguns from other metal or from normal variations in body temperature, and thus is subject to an excessive amount of false alarms. Earlier expectations have not been met.

c. Radar-Radiometry System. A combination radar-radiometry system has some possibility of distinguishing weapons. Whether it would be better than magnetometers is unknown.

d. High Range Resolution Radar. It may be possible to develop extremely short-pulse, high range resolution radars which could produce distinctive returns useful for weapons detection.

3. Chemical Detection Systems

a. Vapor-Emission Analysis. Chemical and physical chemical systems under development for the detection of firearms and explosives are designed to be sensitive to the natural vapor emissions from explosives, gun oils, powder residues, cleaning solutions or marking additives. Detection of firearms by means of vapor emission analysis is not possible by today's state of the art, and it is unlikely that further R&D effort will improve this situation. Explosives detection usually involves detection of vapors with dilutions of at least one part in 10^9, even if the "bomber" makes no effort to reduce vapor emissions. Several systems with such sensitivity are operational for dynamite detection, and one for TNT detection. Three other prototypes show great promise. Improvements in pre-concentration techniques would permit the development of more widely applicable systems (i.e., effective against a greater variety of explosives). All vapor-sensing systems would be vulnerable to sophisticated sabotage techniques that would hermetically seal the explosives portion of a bomb. Also,

provocateurs could overwhelm the vapor detector by the use of simulants. For this reason, FAA monitoring of ongoing vapor-emission analysis projects would seem sufficient for the present.

b. Neutron Activation Analysis. Neutron activation techniques appear to offer the means by which all nitrogen-based explosives (essentially all readily available explosives) contained in luggage-sized containers could be detected. The principal difficulties here are in engineering development and test evaluation as well as in resolution of the question of activation of consumables.

4. Metal Detection

Active metal detectors have been developed that have a capability of detecting handguns with a probability in excess of 90 percent and with a false-alarm rate less than 10 percent. Improvements will require more sophisticated instrumentation and measurement techniques, and the degree of improvement is uncertain. The improvements, if successful, would probably yield the most economical and effective sensing device.

5. X Rays

A low-dose, flying-spot, scanning X-ray system has been developed for baggage inspection and could be developed for personnel inspection. Dose levels would be less than 0.1 mrad. Such a dose does not appear to be unreasonable from a technological or biological risk standpoint, if exposure of only some small fraction of the flying population would be required. Such a restraint might, however, degrade its operational effectiveness. An unmanned contrast detection system could be developed to reduce the operating costs required to observe an X-ray imaging system.

6. Imaging Radar

The use of radar at millimeter wavelengths for obtaining an image of a concealed weapon is a possibility. A prime problem concerns backscatter from the body. Holographic techniques, particularly phase-only holography, offer some unique potentials for concealed weapons detection.

In principle, holography has the ability of obtaining a single three-dimensional image of the object that can be inspected from different directions long after the object has been removed. Problems of dynamic range, resolution, contrast, and real-time detection and image reconstruction remain to be resolved, as well as operational utility and cost.

Imaging of concealed weapons at millimeter wavelengths with dielectric lenses is being sponsored by the Electronics Command, Department of the Army. Initial results are promising. The problems are similar to those encountered with holographic techniques. The technology is somewhat simpler since the image is produced directly.

7. Infrared

Some new transmission measurements suggest that an IR imaging system is a potentially feasible method for detecting weapons concealed by clothing. Systems are available for operation in the 8-14 micron band such as the military forward-looking infrared (FLIR) systems and the medical thermoscopes, but clothing is opaque at these wavelengths. On the other hand, clothing is semitransparent at 500 microns, but considerable effort would be required to develop the components required by a system operating at this wavelength. Conceptually, images of adequate quality could be obtained.

8. Nonlethal Weapons

Realistic scenarios show that hijacking has almost always invoked lethal hazards, and the problem is to prevent either single or mass murder by incapacitating the hijacker before he can take fatal action. If there is a life-and-death requirement to paralyze his weapon hand, the hijacker can be collapsed with high-voltage electrical pulses, provided the Taser projector can be brought within range, aimed, and fired before the hijacker reacts. Mace is not as incapacitating as the Taser but it is equally fast and also subject to projector range and aiming limitations. It could be most effective if employed by trained crew members or a skymarshal at close range in situations where the hijacker has no access to lethal force. With each of these

weapons there is an obvious requirement to train personnel in their proper use and in how to deal with passengers who may inadvertently suffer their effects.

B. FINDINGS

It remains for us to distinguish from among promising techniques those that afford the most readily available capabilities and to select the program directions most likely to develop new capabilities. Admittedly, some of our evaluations will be judgmental. We cannot be sure of the relative effectiveness of the various sensors, as experimental data are lacking for many. Nevertheless, there is enough evidence to give useful guidance.

Table 18 offers a comparison of the various sensory techniques investigated and indicates recommended R&D program elements. The actual or postulated applicability of each technique to the detection of weapons or explosives is considered. "Probability of Detection" refers to estimated capability after needed research and development is essentially completed. The estimated costs shown under "Research" are for those activities listed under "Recommended Program Elements" and do not represent the entire R&D cost required to obtain an operational prototype. Estimates of measurement costs assume that instrumentation is already available at no expense.

For the detection of explosives, the only techniques showing any capability are the use of dogs, chemical analysis, and neutron activation. Much needs to be learned about dogs' sensitivity to vapors of explosives and how to train and maintain their efficiency detection. Chemical vapor sensor programs are under way at LWL and MERDC. Fast neutron activation analysis studies are under way and the use of thermal neutrons appears as a new possibility.

For the detection of weapons, particularly handguns, metal sensing techniques continue to offer the most promise when performance, cost, safety, and availability are all considered. Evidence of possible

TABLE 18. SUMMARY COMPARISON OF DETECTION TECHNIQUES AND RECOMMENDED PROGRAM ELEMENTS

Technique	Detection of		Probability of Detection	False-Alarm Probability	Estimated Cost, thousands		Recommended Program Elements
	Weapons	Explosives			Research	Sensor (Each)	
Nonimaging							
Physiological Observation	•	•	Low, Low	High, High	$ --	$ --	None.
Dogs	?	•	?, Medium	?, Medium	200	2	Test and train.
Mass Detection	•		Low	High	--	--	None.
Microwave and Millimeter-Wave Detection							
Radar	•		Low	High	--	--	None.
Radiometry	•		Low	High	--	--	None.
Radar-Radiometry	•		Medium	Medium	100	?	Measurements.
High Range Resolution Radar	•		Medium	Medium	100	?	Measurements.
Chemical Detection							
Sniffers		•	Medium	Low	200	15	Monitor.
Neutron Activation		•	High	Low	300	?	Engineering, test.
Metal Detection	•		High	Medium	200	20	Measurements and analysis.
Imaging							
Television in the Visible Spectrum	•		Low	Low	--	--	None.
Magnetic Mapping and Display	•		Low	?	--	--	None.
Ultrasonics	•		Low	Low	--	--	None.
X Rays	•		High	Low	200	25	Establish dose limits, flying spot for people.
Radar							
Millimeter-Wave Lens System	•		Medium	Medium	100	100	Monitor.
Millimeter-Wave Holography	•		Medium	Medium	100	50	Measurements.
Infrared	•		Medium	Low	100	100	Measurements.

improved gun detection capabilities from multiple-measurement metal detection devices is still inadequate. X-ray techniques still offer the best of the imaging possibilities but impose a small X-radiation dose (~ 0.1 mrad). Imaging radar and IR in the 100- to 1000-micron wavelength range offer interesting new possibilities, but information is needed to determine whether these techniques can penetrate clothing in times short enough to be operationally useful.

Of the nonlethal weapons surveyed for aircrew and skymarshal use against hijackers, the Taser electric shock weapon and chemical Mace appear to merit consideration.

Before we present our recommendations, it is well to recall the caveats listed in the introduction. The weapons sensors we have considered, with the possible exception of X rays, are limited to the detection of metallic weapons and are not suitable for the detection of wood, plastic, or similar material.

The major concern of this paper has been to consider the technical feasibility of developing various sensors rather than to evaluate their impact upon the processing of passengers in an airport setting. To a large extent, questions concerning the use of such devices are premature until it is reasonably clear that they can be developed and made to operate in a reliable fashion. Nevertheless, it can be foreseen that certain practical problems could arise with the use of certain of these devices. For example, public acceptability is a relevant issue, especially with the use of X rays and possibly radar. If dogs are used for detection of explosives, arrangements have to be made for their scheduled duty and for their quartering and handling during off-duty hours. If X rays are used, there would be a need for shielding operational personnel and, perhaps, a requirement for periodic medical examination. If chemical-sensing (i.e., vapor-collection) devices are employed, there may be a need to modify ventilation equipment so that the volumes to be sampled can be collected and measured. If imaging devices (e.g., TV, X ray, or IR) are used, personnel are needed to observe the displays. It is known that observers cannot do

this job well for long periods of time, and there would be a need to rotate personnel on such duty. It may even prove quicker to frisk a suspect than to arrange for several displays from an imaging system. Operational costs for many of the systems are both unknown and difficult to estimate at our present state of knowledge. Essentially, operational problems may well arise, but detailed consideration of such issues are beyond the scope of this study.

C. RECOMMENDATIONS

The recommendations in this report are addressed to the FAA with the goal of developing techniques that could reduce the likelihood of airliner hijacking and the illegal boarding of explosives on aircraft. It is recognized that many, if not all, of these recommendations could be addressed to the other departments or agencies of government that also have significant interest and responsibility in the development of techniques for the same purpose. No attempt is made here to apportion responsibility among departments and agencies. It is assumed that the FAA (or DOT) would take the lead in initiating or monitoring the program activities recommended.

Our recommendations are based on our appraisal of future operational capabilities, on some consideration of R&D, acquisition, and operating costs, and on an implicit (and perhaps very subjective) assessment of operational utility. They are arranged below under each heading in the order of their priority.

1. Explosives Detection

The following activities are recommended in the area of explosives detection:

1. The program to appraise the capabilities of dogs (and dog training) should be expanded, drawing on ongoing programs in the United States.
2. The fast neutron activation analysis programs for examining packages and luggage should be expanded. Further, an

alternate technique using thermal neutrons should be given a feasibility evaluation test.

3. Work by the Department of the Army on chemical analyses of explosives' vapors could become important and should be monitored and supported to ensure consideration of airport application.

2. <u>Weapons Detection</u>

The following activities are recommended in the area of weapons detection:

1. As X ray is the only technique that offers immediate promise of gun detection without frisking, one or two flying-spot, scanning X-ray devices designed to examine humans should be constructed. At one or two large airports procedures should then be developed and tested to facilitate the use of such devices to inspect volunteers and to determine their operational effectiveness and false-alarm characteristics.

2. Experimental measurements and tests should be undertaken to determine the spectral transmittance of clothing at wavelengths from 100 to 1000 microns. This program should be accompanied by a determination, at the same wavelengths, of the emissivity of weapons and the human epidermis to establish the required IR system sensitivity.

3. Experimental measurements and tests should be undertaken to develop an automated, scanning X-ray contrast system of low dosage (< 0.1 mrad) for the detection of bullets and handguns on people and in baggage.

4. Experimental measurements and tests should be undertaken to initiate a new and expanded program to establish the capabilities of metal detector systems. This program should be accompanied by a theoretical analysis of the magnetic perturbations of a variety of metallic shapes to aid in establishing sensitivity limits and instrumentation approaches.

5. Experimental measurements and tests should be undertaken to determine the feasibility of millimeter-wave holographic systems for detecting and distinguishing concealed metallic weapons.

6. Experimental measurements and tests should be undertaken to evaluate the performance of liquid-helium-cooled detectors in a passive imaging IR system or the performance of a laser with uncooled detectors in an active imaging system.

3. Nonlethal Anti-Skyjacker Weapons

To improve the safety of the anti-skyjacker weaponry available to aircrews and skymarshals, it is recommended that:

1. The Taser electric shock weapon be thoroughly tested as to hazard, effectiveness, and operational utility in providing an instantaneous knockdown capability.

2. Range and aiming characteristics of the Taser weapon be measured. If the Taser proves accurate, it could serve as an alternative to the gun in knockdown power.

3. Mace could serve as a further option. There is little need for further research and development on Mace.

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DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

WASHINGTON, D.C. 20590

Contract DOT-OS-10017
Task Order No. 3

FEDERAL AVIATION ADMINISTRATION

SCOPE OF WORK

ANTI-HIJACKING AND AIRCRAFT PROTECTION TECHNOLOGY

I. BACKGROUND:

There exist a number of techniques for weapon and explosive detection which, a priori, would seem to offer at least some promise in helping resolve the hijacking and aircraft protection problem. Also there are a large number of proposals that claim to have pertinent capabilities. Unfortunately, not enough is known in quantitative terms to appraise preferable courses of action. An immediate problem is the need to acquire a base of technical and operational knowledge to permit a rational comparison of the many potential alternatives. A program of measurement and feasibility testing is indicated in order to give a basis for RFP preparation and judgment of future procurement.

The problem is compounded by the fact that a substantial number of government agencies have allied interest. To name a few there are the Department of Defense, Federal Deposit Insurance Corporation, Secret Service, Department of Justice, Federal Bureau of Investigation, Treasury Department, Customs, etc.

II. STATEMENT OF WORK:

The purpose of this effort is to appraise the technical promise and feasibility of various methods of protecting aircraft against hijacking and the unlawful boarding of explosives, and recommend experimental and test programs and evaluate the results where appropriate.

An attempt shall be made to consider all means of detecting the possibility of hijacking.

As a minimum, this shall include:

a. A review and updating of IDA S-332, "On the Detection of Concealed Hand Guns," and preparation of recommendations for a desirable program of experiments and research to improve the capability of detecting concealed guns and other potential weapons on passengers.

b. A review and evaluation of potential means to detect the presence of damaging explosives in baggage, freight, or airplane prior to takeoff of aircraft.

c. A review of operational aspects of the problem in order to indicate experimental and test programs designed to establish operational requirements and operational capabilities for sensors and other techniques.

d. A compilation and analysis of the experiences airlines have had to date using interim protection techniques and procedures.

e. A study of desirable non-lethal weapons by use for air crews based on constraints furnished by Federal Aviation Administration (F.A.A.).

III. OUTLINE OF STUDY FINDINGS AND INITIAL RECOMMENDATIONS:

No later than six (6) months from 1 March 1971, the Institute shall submit five (5) copies of an outline of the study findings to date and the initial recommendations. Four (4) copies shall be sent to the Contracting Officer's Technical Representative and one (1) copy shall be sent to the Contracting Officer.

IV. REPORTS:

No later than 28 February 1972, twenty-five (25) copies of a technical report, informal letter type, shall be delivered. Twenty-four (24) copies shall be sent to the Contracting Officer's Technical Representative and one (1) copy shall be sent to the Contracting Officer.

APPENDIX B

NATURAL AND MAN-MADE ENVIRONMENTAL RADIATION AND RADIATION-INDUCED CANCER

CONTENTS

I. NATURAL BACKGROUND RADIATION

The general population is exposed to two major sources of ionizing radiation: (1) natural background and (2) artificial or man-made radiation. It is enlightening to compare the magnitude of the X-ray dose from an anti-hijacking X ray to those radiation doses that the general population is already voluntarily or involuntarily absorbing from natural sources. Such a dose comparison should provide a conservative index of the relative risk involved in the potential use of anti-hijacking X rays if the validity of a linear dose-response relationship is assumed.

Man is being continuously exposed to an external and internal natural radiation background. The external background consists almost entirely of cosmic rays and terrestrial radiation from potassium ^{40}K, thorium ^{232}Th, and uranium in the soil. At sea level, the dose from cosmic rays is approximately 50 mrad/yr, and a typical terrestrial dose is also 50 mrad/yr (Ref. B-1). The large changes of terrestrial dose in transiting from one locale to another is illustrated by the measurements obtained from road readings in three cities of Scotland. From Fig. B-1 (Ref. B-2), it is seen that the average road reading was 48.5 mrad/yr in Edinburgh and 104 mrad/yr (more than double the Edinburgh reading) in Aberdeen. A large fluctuation in dose within a given city is also apparent. In Aberdeen, as the survey moved in from the suburbs, with relatively wide roads and a lower density of houses, to the more densely built up central zone, the average half-mile zone dose rate increased from 75 mrad/yr to 113 mrad/yr (Fig. B-2). In Figs. B-1 and B-2, the 0.5-mrad dose per year that would be received from five anti-hijacking 0.1-mrad X rays per year is indicated as an illustration of how small the dose received by a frequent user of commercial aircraft would be in comparison to the fluctuations that he

encountered daily on the ground from his natural background radiation environment.

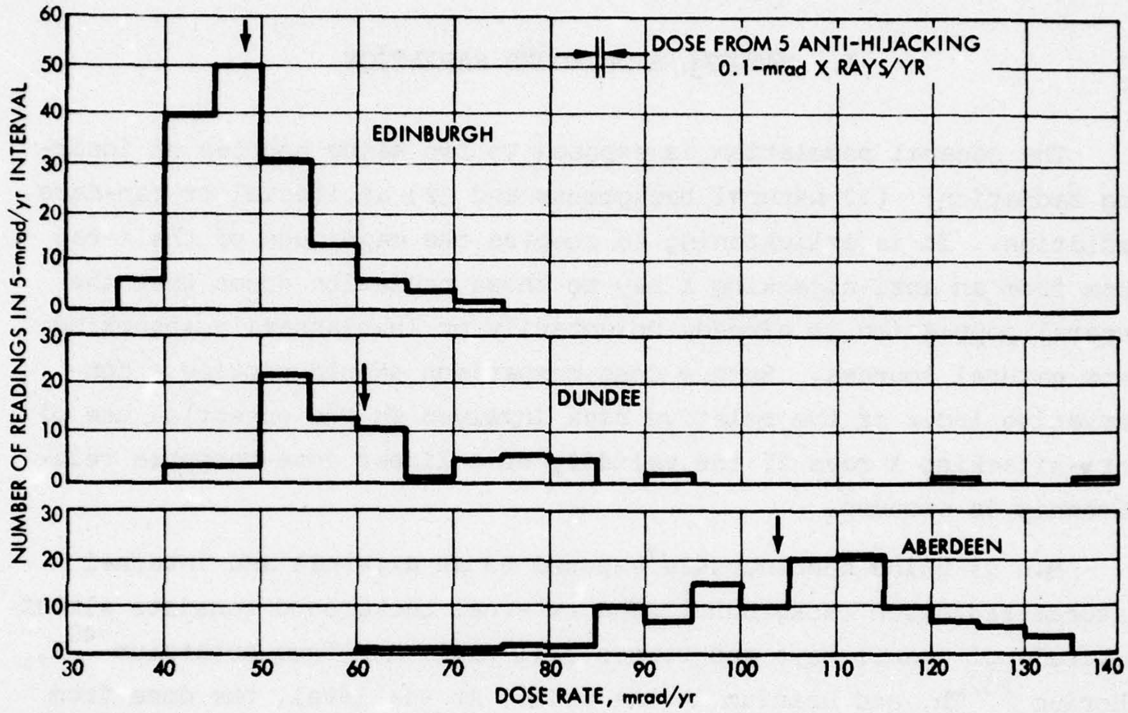

FIGURE B-1. Road Readings (Exclusive of Cosmic-Ray Radiation) in Three Cities of Scotland (Ref. B-2)

The differences in the radiation absorbed by individuals living and working in buildings of different materials is also likely to be much greater than the dose from five anti-hijacking X rays per year. This is illustrated in Fig. B-3 (Ref. B-2) by readings from the same three cities in Scotland in houses built of local stone. The 87-mrad/yr mean dose rate in the Aberdeen granite houses, as in the case of the road readings, is nearly twice the average in the Edinburgh stone houses. Dose rates in clay-brick houses in the three cities were not statistically different and averaged 75 mrad/yr.

The magnitude of the natural background radiation environment in Scotland is typical of that to be found in most areas of the world. However, there do exist a few places, e.g., India and Brazil, where

the soils are so rich in thorium and uranium that the natural background may be as high as 2 rad/yr (Ref. B-3). Tourists sunning themselves on the beaches of Espirito Santo, Brazil, receive a dose as high as 5 mrad/hr, which is equivalent to a 44-rad/yr background radiation environment (Ref. B-4). Average natural background dose rates for some U.S. towns range from 102 to 128 mrad/yr in Colorado; from 58 to 81 mrad/yr in Michigan, and from 73 to 83 mrad/yr in Minnesota (Ref. B-5).

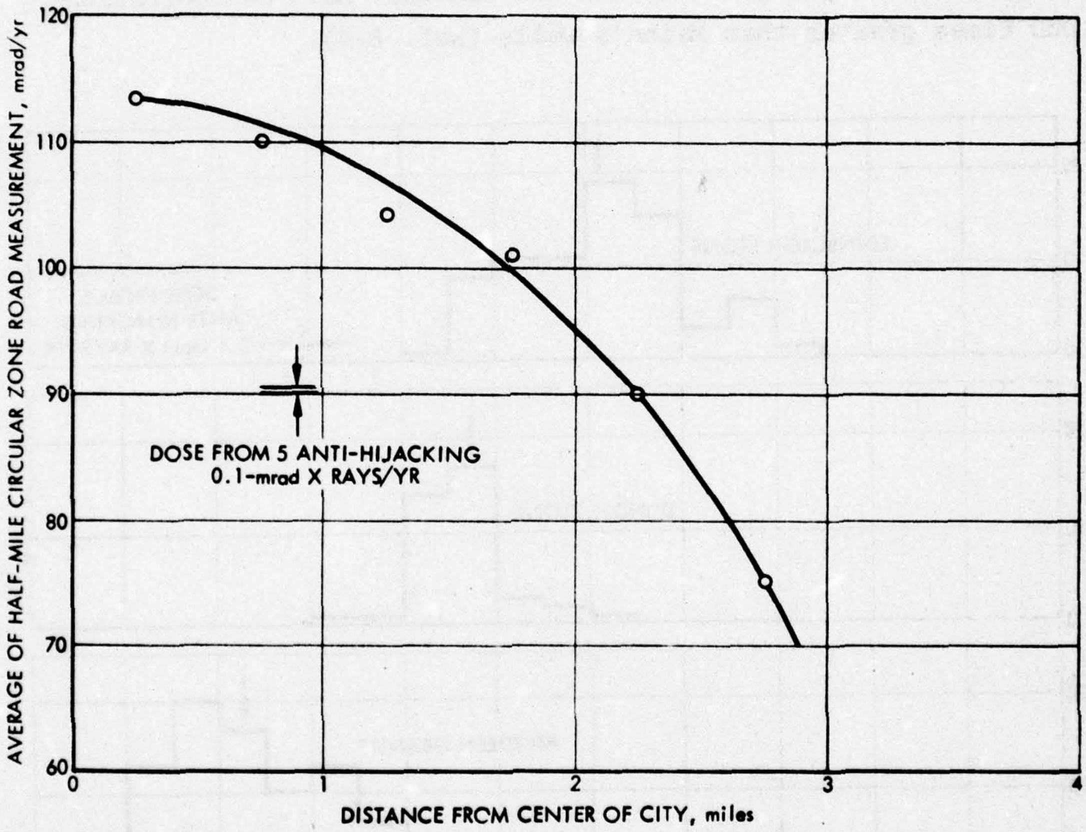

FIGURE B-2. Aberdeen Road Readings (Exclusive of Cosmic-Ray Radiation) versus Distance from Center of City (Ref. B-2)

Internal background radiation exists in the naturally radioactive nuclides which find their way into the body. Potassium-40 (20 mrad/yr), carbon-14 (2 mrad/yr), and tritium (2 mrad/yr) are the most important (Ref. B-3) of those elements which are to be found in the tissues of

the body. Radioactive thorium and uranium and their daughters may be ingested in well water with dose rates of 40-400 mrad/yr (Ref. B-3). Fortunately, these elements pass through the body rapidly. Radium, however, resembles natural calcium so much that it tends to pile up in our bones. There is great variability in the concentration of radium in water supplies. Water from Maine's wells, for example, has 3000 times the radium concentration of the Potomac River, serving Washington, D.C., while some springs in Kansas and Colorado have concentrations 10,000 times greater than Maine's wells (Ref. B-4).

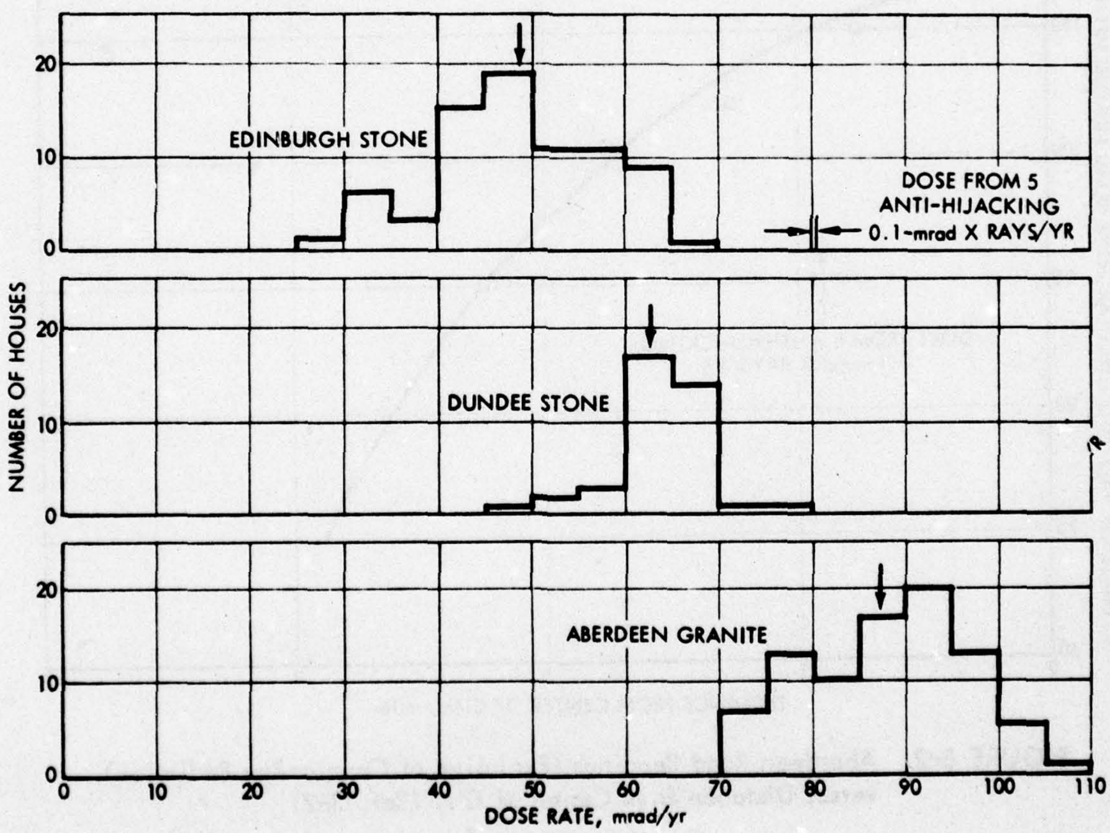

FIGURE B-3. House Readings (Exclusive of Cosmic-Ray Radiation) in Three Cities of Scotland (Ref. B-2)

The air we breathe is another source of natural radiation, with an estimated dose of 5 mrem/yr* to the gonads (Ref. B-1). However, the lungs may receive a dose of 125 to 1570 mrem/yr from radon (alpha particle radiation) given off by building structures, depending upon ventilation conditions and differences in building materials (Ref. B-6).

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*The rem (roentgen equivalent, man) is a measure of the biological effects of radiation, and is obtained by multiplying the rad (radiation absorbed dose), which is defined as the absorption of 100 ergs per gram of absorbing material, by the relative biological effectiveness (RBE) of the radiation. A rad of X rays, gamma rays, or beta particles has a rem of 10 to 20 (Ref. B-1). The RBE of cosmic-ray protons, the major radiation contributor at altitudes under 100,000 ft, may be taken as unity (Ref. B-8). Fast and thermal neutrons have RBE values of 10 and 4.5, respectively (Ref. B-9). The roentgen (r) measures the intensity of radiation and is the amount of X rays or gamma rays which will ionize 2.08×10^9 atoms in 1 cubic centimeter of dry air. A detailed discussion of some difficulties inherent in the definitions of these radiation units may be found in Ref. B-7.

II. MAN-MADE RADIATION

Today the radiation absorbed in medical diagnostic X rays is the only man-made source of radiation which is comparable in magnitude to that of the natural background. Indeed, the portion of the human body irradiated by the X-ray beam may receive a dose one or two orders of magnitude higher than that received in a year from the natural background. From Table B-1 (Ref. B-7) it is seen that the typical skin dose per examination can range from 0.15 rad for a whole chest X ray to 10 rads for a pelvimetry examination.

TABLE B-1. SKIN DOSES IN DIAGNOSTIC EXAMINATIONS (Ref. B-7)

		kv	Typical Skin Dose/ Examination, rad
Head		70	1.3
Cervical Spine		65	0.6
Barium Swallow	Rad.	85	1.4
	Fluor.	85	6.4 r/min
Arm and Hand		55	1.7
Whole Chest		65	0.15
		80	2
Barium Meal	Rad.	85	1.7
	Fluor.	80	4.3 r/min
Cholecystography		70	1.5
Abdomen		75	1.4
Obstetric Abdomen		85	3.8
Intravenous Pyelography		70	1.7
Retrograde Pyelography		75	1.4
Salpinography	Rad.	78	1.2
	Fluor.	78	3.4 r/min
Pelvimetry		90	10
Cystography		76	3.1
Barium Enema	Rad.	85	1.4
	Fluor.	80	4.9 r/min
Pelvis		70	2.1
Lumbar Spine		80	4.5
Lumbar Sacral Joint		75	5.8
Hip		65	1.4
Cardiac Catheterization and Angiocardiography		135	7.0

It is estimated that more than 90 percent of all man-made radiation exposure today is from medical diagnostic X rays and that, unfortunately, at least 90 percent of that is needless (Ref. B-10). For example, it has been estimated that restricting the X-ray beam to an area no larger than that of the film size would result in a reduction of the Genetically Significant Dose* (GSD) from 55 to 19 mrad/yr per person (Ref. B-10). Widespread adoption of other techniques, such as the use of a scanning X-ray system, would further drastically reduce the man-made radiation dose received by the population.

The distribution of the GSD has been found to be highly sex dependent. In the United States, 82 percent of the GSD for medical roentgenology is contributed by males, 16 percent by females, and 2 percent by fetuses (Ref. B-11). The mean gonad dose from medical roentgenology is strongly dependent on age as well as sex, as indicated by Fig. B-4 (Ref. B-11). Males 15 to 29 years of age account for 61 percent of the total GSD. A few high-dose examinations, such as lumbar and lumbosacral spine, barium enema, intravenous or retrograde phyelogram, and pelvic and abdominal examinations, are the principal contributors to the GSD. The reason for the much larger contribution of the male population to the GSD is the significantly greater amount of radiation absorbed by overlying tissue for ovarian doses compared to testicular doses.

The estimated number of medical radiographic films taken in the United States during 1964 was 232 million, with an additional 48 million spot films taken during fluoroscopic examinations (Ref. B-11). An average of 2.2 films per radiographic examination were taken. The estimated percentage distribution of radiographic examinations by body area is indicated in Fig. B-5. The anti-hijacking X ray differs from medical X rays in that irradiation of the entire body is required.

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*That dose which if received by each and every member of the population would have the same genetic effect on the total population as the sum of the individual doses to the particular members of the population.

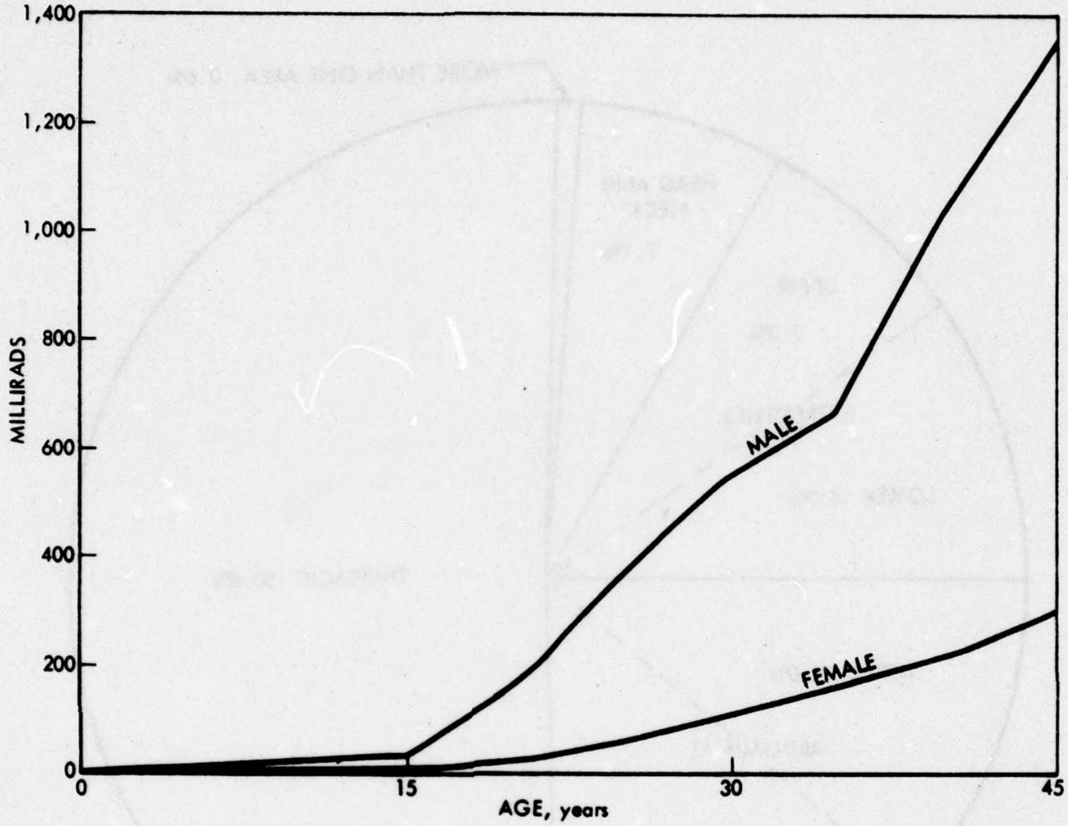

FIGURE B-4. Estimated Accumulated Mean Gonad Doses from Diagnostic Medical Roentgenology by Age and Sex, United States, 1964 (Ref. B-11)

A proper calculation of the GSD is a somewhat complex statistical problem, as can be seen from the formula used in Ref. B-11:

$$\mathrm{GSD} = \frac{\sum_i \sum_j \left[\left(\underbrace{\hat{N}_{ij} P_i D_{ij}}_{\text{male}}\right) + \left(\underbrace{\hat{N}_{ij} P_i D_{ij}}_{\text{female}}\right) + \left(\underbrace{\hat{N}_{ij} P_i D_{ij}}_{\text{fetus}}\right)\right]}{\sum_i \left[\left(\underbrace{N_i P_i}_{\text{male}}\right) + \left(\underbrace{N_i P_i}_{\text{female}}\right) + \left(\underbrace{N_i P_i}_{\text{fetus}}\right)\right]}$$

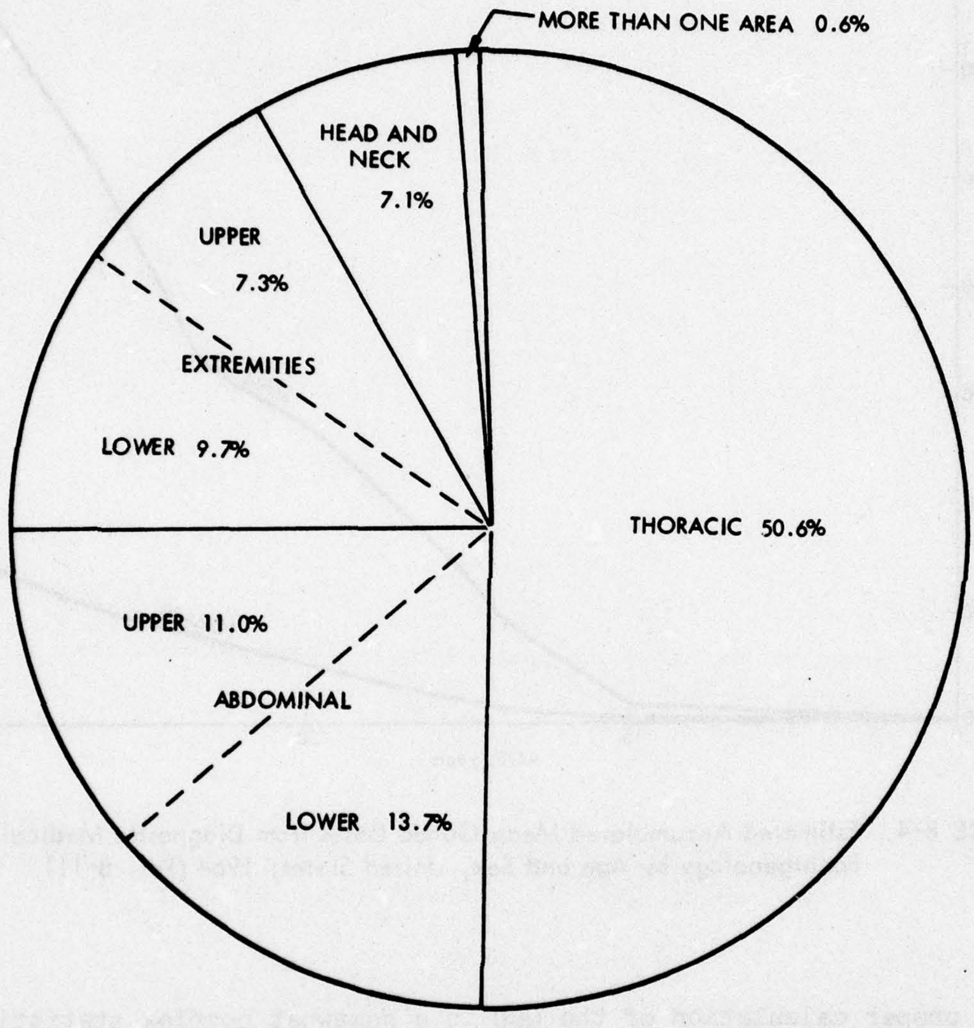

FIGURE B-5. Estimated Percentage Distribution of Radiographic Examinations by Body Area, United States, 1964

where

D_i = the average gonad dose to persons of age i who receive X-ray examinations,

$\hat{N}_i$ = the number of persons in the population of age i who receive X-ray examinations,

P_i = the expected future number of children for a person of age i,

N_i = the number of persons in the population of age i, and

j = indexes type of examination performed.

The somatic effects of ionizing radiation are less well understood than the genetic effects. The relationship between radiation and leukemia for high doses was demonstrated by atomic-bomb survivors at Hiroshima, in studies of patients suffering from ankylosing spondylitis who were treated by radiotherapy, and in studies showing a statistically significant increase in the incidence of childhood leukemia and malignancies following X-ray examination in utero (Ref. B-7). It is believed that the dose to the active bone marrow is the pertinent parameter with respect to the induction of leukemia by radiation. Two estimates of per capita annual mean bone marrow dose from medical diagnostic X rays are 50-100 mrem (Ref. B-6) and 125 mrem (Ref. B-12).

The X-radiation emitted by color television is another source of man-made radiation which fortunately contributes a GSD that is at most an order of magnitude less than the medical diagnostic X-ray dose. The National Council on Radiation Protection (NCRP) recommends that the exposure rate at any readily accessible point 5 cm from the surface of any home television receiver shall not exceed 0.5 mr/hr under normal operating conditions (Ref. B-13). If every TV receiver is assumed to emit the recommended 0.5 mr/hr, a simple calculation of the dose can be made, as indicated in Table B-2 (Ref. B-13).

At a typical viewing distance of 200 cm, the dose falls off to 0.01 mr/hr.* The mean depth of the testes and ovaries was assumed at 1 and 5 cm, respectively, and the average viewing time at 20 hr/wk.

*Not inverse square, since the source of radiation is not a point.

The resulting 4.5-mrem/hr TV receiver contribution to the GSD is an overestimate. This is apparent from a survey of 1,124 color television receivers in the Washington, D.C., metropolitan area conducted by the National Center for Radiological Health (NCRH) during December 1967 and January 1968. Of these sets, 66 emitted X rays at exposure rates at or in excess of the recommended level of 0.5 mr/hr. These emissions were reduced through service adjustments, such as replacement of shunt regulator or rectifier tubes and reduction of the operating high voltage. The minimum detectable signal was 0.04 mr/hr, and 856 of the 1,124 receivers surveyed emitted no measurable levels of X radiation. A defective TV tube can be extremely hazardous. A defective GE 6EF4 tube, under operating conditions to produce maximum X-ray emission, produced an exposure rate of 83 r/hr immediately at the floor level under a console receiver, and a calculated maximum exposure rate of 800 r/hr below the receiver (Ref. B-14).

TABLE B-2. CONTRIBUTION* OF TV RECEIVERS TO THE GENETICALLY SIGNIFICANT DOSE OF THE POPULATION

	mr/hr	mrem**/yr
At 5 cm	0.5	
At 200 cm (2 percent)	0.01	
At 1 cm depth (depth of dose = 75 percent)	0.0075	
At 5 cm depth (depth of dose = 11 percent)	0.0011	
Average	0.0043	
Per capita gonad dose, if average viewing time = 1000 hr/yr (20 hr/wk)		4.3

*From front of picture tube of receivers meeting the 0.5-mr/hr limit.

**The number of millirems may be assumed to be equal to the number of milliroentgens.

In comparing the somatic effects of X radiation from TV with that of medical diagnostic X rays, an important difference should be noted. The X-ray emission from a color TV receiver has three components: (1) the picture tube, (2) the shunt regulator tube, and (3) the rectifier tube. The photon energy spectrum for a typical color TV receiver operating at 25 kv is shown in Fig. B-6 (Ref. B-15). Approximately 90 percent of this 25-kev radiation is absorbed in a body depth of 4 cm, as indicated in Fig. B-7 (Ref. B-16), which measured depth dose with a water phantom irradiated by a therapy X-ray unit (Picker "Zephyr" Model NR-2). The X-ray tube was operated at a lower voltage than is usual, and the primary beam filtration was adjusted to effect a good approximation to the spectra of a color TV receiver. In the case of medical diagnostic X rays, voltage settings typically range from 65 to 110 kv to effect a penetration of the body thickness. The greater penetration capability of these higher energy photons is illustrated in Fig. B-7. This suggests that color TV receiver radiation may principally affect the lens of the eye, the male gonads, the bone marrow, and the skin (Ref. B-17), whereas in diagnostic medical X rays all body organs are affected to a degree dependent on their location in the body.

Another source of man-made radiation of increasing national concern is the nuclear power plant. The dietary dose, and in particular the strontium-90 bone dose, is the major contributor to the population dose from a nuclear fuel service. Based on surveys carried out by the New York State Department of Health, the U.S. Public Health Service, and the Atomic Energy Commission, the dietary strontium-90 dose to a "typical individual" around a nuclear fuel service in New York State in 1968 was estimated at 77 millirem per 50 years of lifetime (Ref. B-18). A "typical individual" is defined as a hypothetical adult ingesting an "average" concentration of specific radionuclides based on environmental surveys. This dose was, therefore, estimated to be approximately 2 percent of the natural background radiation dose.

The Federal Radiation Council (FRC) recommends 500 mrem/yr as the maximum permitted bone dose and 170 mrem/yr as the maximum permitted

whole-body dose. It is believed by some scientists that the FRC recommendations should be revised drastically downward. One estimate (Ref. B-19) of the additional cancer cases per year in the United States from an additional 170-mrad dose to the population at large is 16,000. Another estimate is 4000 to 5000 (Ref. B-10).

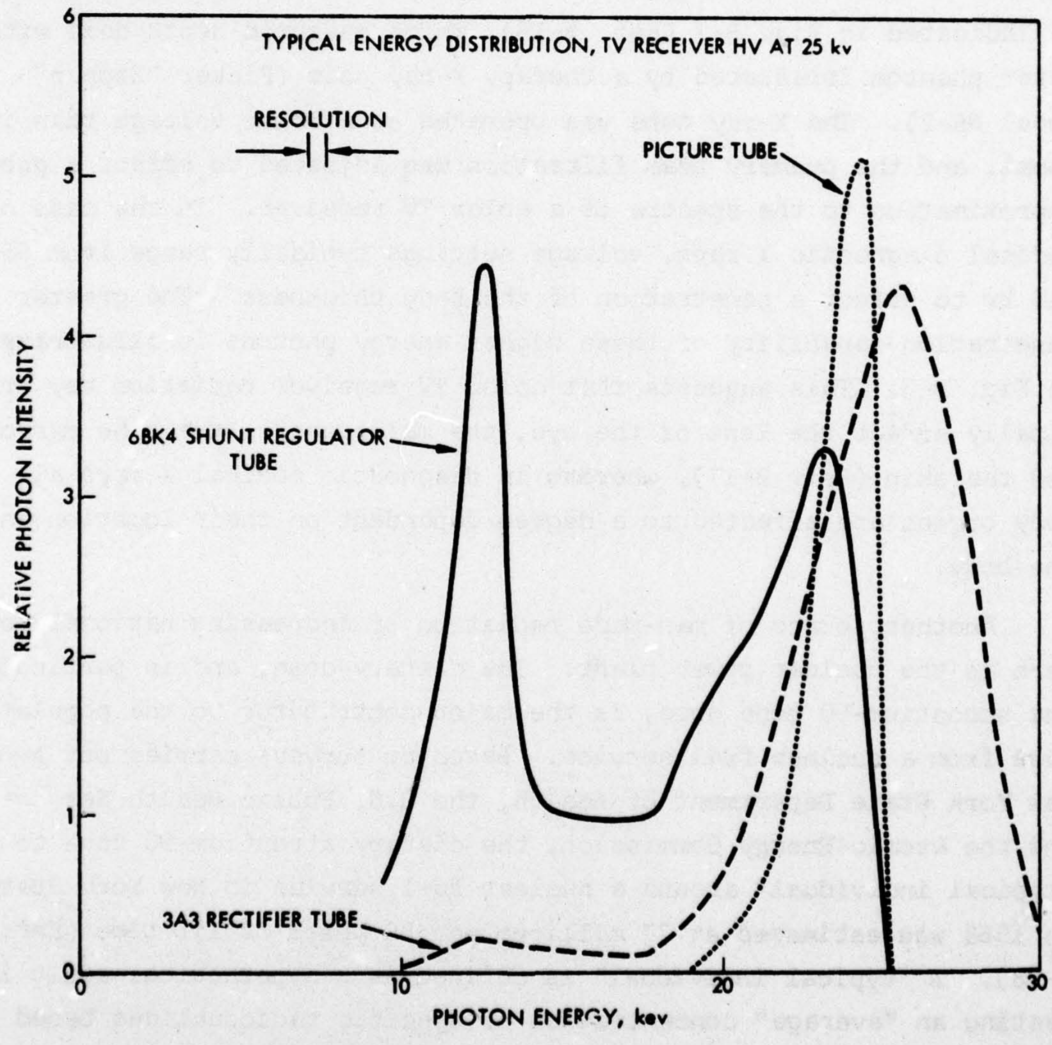

FIGURE B-6. Typical Energy Distribution, TV Receiver HV at 25 kv (Ref. B-15)

Finally, there exists that undesirable man-made radiation hazard to the population from nuclear weapons fallout. A 1966 estimate of the average annual exposure to the gonads from fallout is 4 mrem (Ref. B-1). This source of man-made radiation will hopefully recede with the continued observance of the Nuclear Test Ban Treaty.

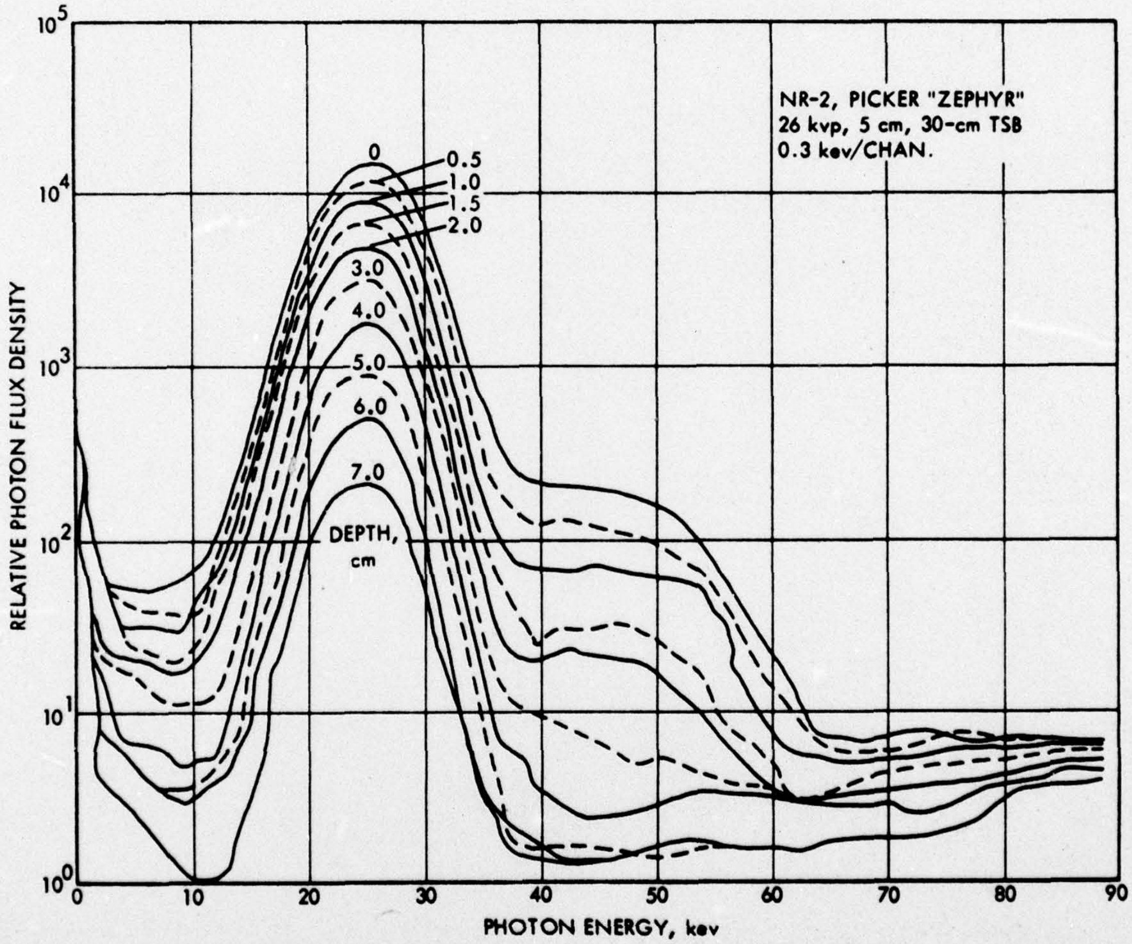

FIGURE B-7. Central-Axis X Ray Spectra at Various Depths in Water Phantom (Ref. B-16)

III. RADIATION-INDUCED CANCER

The mechanism by which cancer is induced in the human body by ionizing radiation is not known at the present time. It is known that chromosomal aberrations are induced by radiation. From Fig. B-8 (Ref. B-20) it is seen that the frequency of chromosomal aberrations in human leukocytes which have been exposed in vitro to X radiation is proportional to the radiation dose. Cancer tissue usually exhibits chromosomal aberrations (Ref. B-20). It is, therefore, a plausible hypothesis that the incidence of cancer is proportional to the radiation exposure level.

The "best estimate" of the percent increase in the cancer incidence rate per year per rad of exposure for all organ sites is given in Table B-3 (Ref. B-19).

TABLE B-3. BEST ESTIMATE OF THE PERCENT INCREASE IN HUMAN CANCER INCIDENCE RATE PER YEAR PER RAD OF EXPOSURE (Ref. B-19)

	Percent Increase in Incidence Rate Per Year Per Rad
Leukemia	1.6 - 3.3
Thyroid Cancer	
(in Adults)	1
(in Young Persons)	10 - 20
Lung Cancer	0.6
Breast Cancer	1
Stomach Cancer	0.4
Pancreas Cancer	0.8
Bone Cancer	2.5
Lymphatic and Other Hematopoietic Organs	1.4
Carcinomatosis of Miscellaneous Origin	1.7

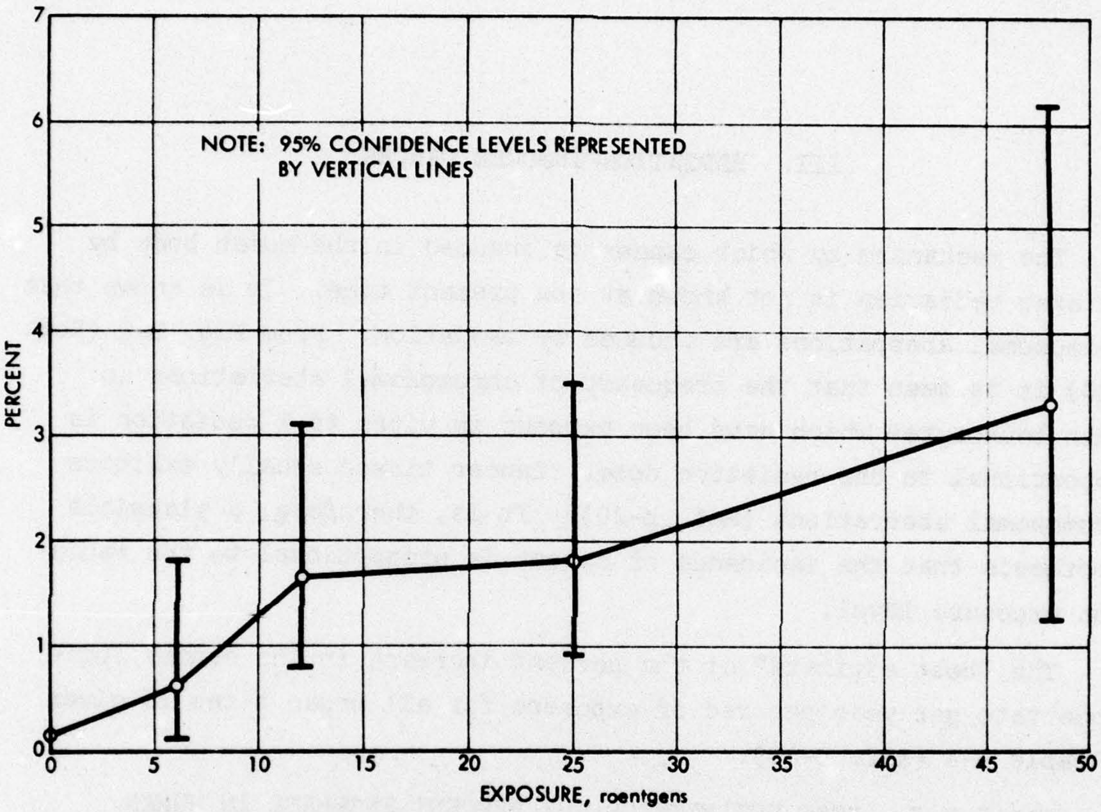

FIGURE B-8. Percentage of Cells Containing Chromosomal Aberrations for Exposures from 0 to 48 Roentgens (Ref. B-20)

There is a surprisingly small range in the estimated increase in incidence rate per year per rad for these widely differing organ sites in which cancers arise.

The cancer incidence rate is, of course, a function of age. In Ref. B-19, the following assignment of incidence rates per year per rad for all forms of cancer was deemed reasonable: 1 percent for adults, between 1 and 20 percent for youthful subjects (< 20 years of age) and 17 percent for infants in utero.

By assuming a linear relationship between dose and effect, as do the national and international agencies that set the radiation protection standards, it has been estimated that there are from 3,500 to

30,000 deaths per year introduced into the population of the United States due to genetic mutations and somatic damage resulting from diagnostic X-ray exposure. This loss of life, although too high, is offset by the hopefully much larger number of lives saved through the use of diagnostic X rays. Although this number may be in the neighborhood of 100,000 lives saved, there is no survey or statistical analysis to support any such number (Ref. B-21). No one doubts, however, that the risk-benefit comparison favors the continued judicious use of medical diagnostic X rays.

The biological effect of radiation dose rate on the body is not well understood. It is known that at very high dose levels a stretch-out in time allows the body time to recover. For example, in an experiment on mice an acute dose of 1000 rads of X rays, which was more than needed to kill all the animals in 30 days, was given in doses of 250 rads spaced evenly in 2-week periods. None of the mice died, and only 15 percent developed leukemia (Ref. B-3). However, one can deduce from Fig. B-9 (Ref. B-22) that at very low dose levels there is likely to be little difference in the effects of chronic and acute radiation. The percentage of human cells in tissue culture which have, after irradiation, retained the capacity for unlimited proliferation is found to be practically independent of dose rate for alpha radiation, but a 250-kv X-ray dose rate of 200 rads/min is more damaging than a dose rate of 0.5 rad/min for equivalent doses. At 50 percent survival, the RBE of alpha radiation for the high-dose rate is 5.3; for the low dose the RBE is 7.4. However, at dose levels in the millirad region the behavior of the curves indicates that the RBE of alpha radiation would be independent of the X-ray dose rate.

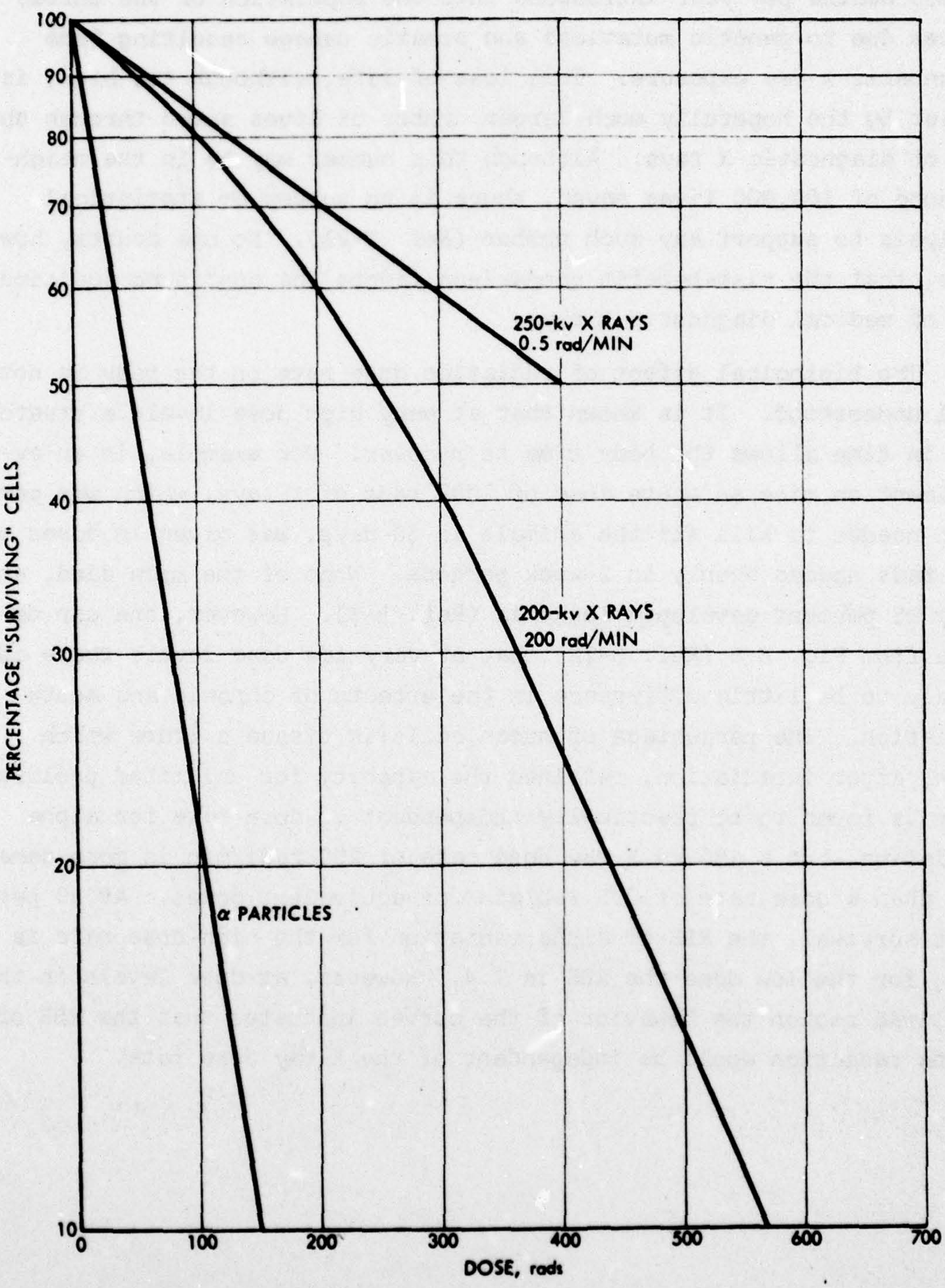

FIGURE B-9. Percentage of Human Cells in Tissue Retaining Capacity for Unlimited Proliferation (Ref. B-22)

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APPENDIX C

MULTIPLE-SENSOR DETECTION SYSTEM

The radiation dose to the flying population may be reduced by designing a detection system that also utilizes information gained from other detection techniques. Depending upon how the information from these detection subsystems is handled, penalties in system performance may be expected in the form of a lower detection probability or a higher false-alarm rate. To illustrate this behavior, consider the case of three candidate detection subsystems: (1) profile or p, (2) magnetometer or m, and (3) X ray or x. Each subsystem detector, when operated singly, will be characterized by a detection probability p_p, p_m, and p_x, and a false-alarm probability f_p, f_m, and f_x, respectively. In the analysis below, values of these parameters are assumed.

The expressions for the system detection probability p_d, false-alarm probability p_f, and X-ray exposure probability p_x are given in Table C-1 for all possible cases in which the three subsystems are used singly, in pairs, and in a combination of all three. Profile screening, when used with the other sensors, is assumed to be the first detection subsystem to be encountered by the subject, the magnetometer next (when applicable), and the X-ray machine last. In the case of two sensors in Table C-1 which are connected by a + sign, the subject must pass through the second sensor if no positive signal is indicated by the first. A positive signal from the first sensor leads to a search, which may result in a detection or a false alarm, as does no positive signal from the first sensor and a positive signal from the second. In the case where the two sensors are connected by a / sign, a positive signal from the first sensor activates the second sensor, where another positive signal must be recorded to justify a search.

TABLE C-1. MULTIPLE-SENSOR DETECTION SYSTEMS

System	p_d	p_f	p_x
p	p_p	f_p	0
m	p_m	f_m	0
p+m	$1-(1-p_p)(1-p_m)$	$f_p+(1-f_p)f_m$	0
p/m	$p_p p_m$	$f_p f_m$	0
x	p_x	f_x	1
p+x	$1-(1-p_p)(1-p_x)$	$f_p+(1-f_p)f_x$	$1-f_p$
p/x	$p_p p_x$	$f_p f_x$	f_p
m+x	$1-(1-p_m)(1-p_x)$	$f_m+(1-f_m)f_x$	$1-f_m$
m/x	$p_m p_x$	$f_m f_x$	f_m
p+m+x	$1-(1-p_m)(1-p_m)(1-p_x)$	$f_p+(1-f_p)[f_m+(1-f_m)f_x]$	$(1-f_p)(1-f_m)$
p/m/x	$p_p p_m p_x$	$f_p f_m f_x$	$f_p f_m$
p/(m+x)	$p_p[1-(1-p_m)(1-p_x)]$	$f_p[f_m+(1-f_m)f_x]$	$f_p(1-f_m)$
(p+m)/x	$p_x[1-(1-p_p)(1-p_m)]$	$f_x[f_p+(1-f_p)f_m]$	$f_p+(1-f_p)f_m$

In Table C-2 the values of p_d, p_f, and p_x are given for the specified sensor-detection and false-alarm-rate parameters to illustrate the manner in which these system performance parameters interact. Two values of p_p, .90 and .50, are assumed in order to investigate the sensitivity of the system detection probability p_d to a degradation in the profile screening effectiveness.

Addition of only a magnetometer to profile screening would seem to be of dubious attractiveness for the assumed parameter values. The p + m system false-alarm rate is (.216), an order of magnitude higher than that of the p system, and the p/m system detection probability is less than that of the p system, which is particularly unsatisfactory in the case of the degraded p system (.45). Addition of an X-ray machine to the p system is also of questionable attractiveness. The p + x system has a very high detection probability (.998) and a low false-alarm rate (.03), but almost every adult male passenger (.98) is X-rayed. The p/x system has a lower detection probability (.882) than the p system (.90). The m + x system has too high a probability of X-ray exposure (.80) as well as too high a false-alarm rate (.208), and the m/x system has a lower detection probability (.882) than the m system (.90). Of the four configurations of the three-sensor system, only the (p + m)/x offers a high probability of detection (.93-.97), even in the case of a severely degraded profile screening effectiveness, low false-alarm rate (.002), and a low probability of X-ray exposure (.216), which corresponds to less than 10 percent of the flying population if women and children are excluded from X-ray exposure.

To properly optimize a multiple-sensor detection system, one should have test information on the detection and false-alarm rate for each candidate sensor, and cost estimates for each candidate sensor, including maintenance and operating costs. The attention that must be paid to the manner in which the information links are interconnected is well illustrated by Table C-2.

TABLE C-2. ILLUSTRATIVE CASE FOR MULTIPLE SENSOR DETECTION SYSTEM

System	Probability of Detection, P_d		Probability of False Alarm P_f	Probability of X Ray P_x
	$P_p = .90$	$P_p = .50$		
p	.90	.50	.02	0
m	.90	.90	.20	0
p+m	.99	.95	.216	0
p/m	.81	.45	.004	0
x	.98	.98	.010	1
p+x	.998	.99	.030	.98
p/x	.882	.49	2×10^{-4}	.02
m+x	.998	.998	.208	.80
m/x	.882	.882	.002	.20
p+m+x	.9998	.999	.224	.784
p/m/x	.7938	.441	4×10^{-5}	.004
p/(m+x)	.8982	.499	.00416	.016
(p+m)/x	.9702	.931	.00216	.216

NOTE: $P_p = .90$ and $.50$

$P_m = .90$

$P_x = .98$

$f_p = .02$

$f_m = .20$

$f_x = .01$